THE
ADVANCING FRONT
OF SCIENCE

THE ADVANCING FRONT OF SCIENCE

by GEORGE W. GRAY

Here stand I as though on a frontier
that divides two peoples, looking both
to the past and to the future.
—*Petrarch, Book of Memorable Things*

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To

JOHN C. MERRIAM

PRESIDENT OF THE CARNEGIE INSTITUTION OF WASHINGTON

A leader in the scientific advance

PREFACE

In a preceding book I undertook to outline the new world picture of modern physics, and to present briefly the sequence of discoveries and of guiding theories by which the new concepts were arrived at. The present book is an attempt to report news rather than to summarize history. It is an account of certain current advances in representative fields of science, of things lately turned up in the skies, in the atoms and molecules, in the living matter of cells and tissues—findings and intimations which are providing the basis for further advances, for reinterpretations, for the new world view of tomorrow. Obviously the experiments and discoveries herein described are only samplings of a vast teamwork in which men of many nations are cooperatively engaged. These chapters are largely concerned with activities in the United States, and particularly with the work of investigators whom I have had opportunity to consult. It would take many books to cover the field in any one of the specialties touched on. But perhaps the samplings can do for the general reader what complete technical treatises do not: convey something of the spirit, the purpose, the ingenious methods, and the accomplishments which make the research laboratory the most romantic spot on the Earth at the present time—and perhaps the most significant. For it is here that the future comes.

Pascal, in one of his *pensées*, has chided those authors who talk of "my book," advising that they would do

better to say "our book, our commentary, our history." The present volume could not have been written but for the generous response, cooperation, and encouragement which the author received from men of the laboratories, and in a quite literal sense this is "our book." I was aided at every turn, first by the open-door policy which admitted me to the research workrooms, then by the interest and patience of the researchers who demonstrated and explained their experiments and results, and finally by those who read and checked the chapters in manuscript. In acknowledging a great debt to these collaborators, I do not wish to imply that they are responsible for any errors or other maladjustments that may have survived the several revisions, or that they endorse the book. The final product is my responsibility, and mine alone. I should also add that the choice of laboratories visited and of work cited is entirely mine.

Each chapter represents contacts with and contributions from several workers. Those to whom I am particularly indebted are the following:

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PREFACE

Certain chapters or parts of chapters have appeared as articles in magazines: the *Atlantic Monthly*, *Esquire*, *Harper's Magazine*, the *New York Times Magazine*, and *This Week*. Thanks are expressed to the editors of these periodicals for releasing the material for its extension and development in book form.

G. W. G.

CONTENTS

THE ADVANCING FRONT OF SCIENCE

Prologue · THE APPROACH TO SCIENCE

> Science has its showrooms and its workshops. The public today, I think rightly, is not content to wander round the showrooms where the tested products are exhibited; the demand is to see what is going on in the workshops. You are welcome to enter; but do not judge what you see by the standards of the showroom.
>
> —ARTHUR S. EDDINGTON, THE EXPANDING UNIVERSE

THE slackened activity in industry and trade, which was the most conspicuous aspect of human relations during the early 1930's, presents a curious contrast with the quickened activity of scientific research. While the bewildered world of affairs was at a standstill, or worse, swept into frantic experiments with discredited social devices, political dictatorships, and nationalistic insularities, science pushed progressively into new fields, into wider sharing of its results, into bolder and more penetrating attacks on the unknowns of nature.

This is not to imply that scientists escaped the privations and anxieties of the economic slump. The truth is far otherwise. Between 1930 and 1934 the American foundations, with endowment funds totaling seven hundred million dollars, suffered such shrinkage of income that their directors deemed it necessary to cut their annual grants for the support of scientific investigations by nearly three-

fourths. During the same period, the United States federal government and many state governments instituted retrenchment policies whose first victims were the publicly supported research centers. Deprivations were even more severe in some European countries. Science was put on short rations. Some laboratories sought and found means of self-support, sacrificing valuable time and talent to financial pursuit, so it would seem. There is scarcely an institution that was not handicapped in some way by the depression. The remarkable circumstance is the accelerated pace of research in spite of these hardships. And the remarkable outcome is the fundamental nature of many of the discoveries made in these years of stringency and embarrassment. The advances of our decade are of such brilliance as to recall the golden years of 1895–1905, when physics stirred from its long lethargy and sounded the call which echoed far and awakeningly along all the frontiers of thought.

The chapters of this book are an account of some of these recent advances. They represent an attempt to present the current news of scientific research promptly, in convenient form, and in terms that will convey the meaning and spirit of the endeavor without indulgence in false emphasis or sensationalism. Such tricks are not only alien to science but unnecessary to its publication, for few subjects are more interesting to the healthy mind than the drama of discovery. Of all the undertakings of man through the ages, the exploration of nature is the one that has progressed consistently toward its objectives, it is the one whose results have served man most directly, and the one that by virtue of both its character and its attainments appeals most surely to the curiosity of the intelligent person. At the same time it is the human activity that beyond all others is the most specialized and, by reason of its standards of exactitude in truth seeking, the most technical in terminology. Therefore, it needs interpretation.

One of the imperative tasks of our day is to interpret the purposes, methods, and results of science in such wise that this greatest adventure of the human spirit may be "understanded of the people." Science needs to be made use of, but understanding of it must precede complete utilization. It needs to be made use of, not only in those practical ways which lighten burdens, relieve pains, cure diseases, and increase the comforts and conveniences of civilized life, but more—it needs to be made use of also in those higher outcomes of the new knowledge: the freeing of the individual from fear and superstition, the widening of intellectual horizons, the strengthening of the ties of mutual interest which alleviate man's inhumanity to man.

"The motive of science," said Ralph Waldo Emerson, "was the extension of man, on all sides, into nature, till his hands should touch the stars, his eyes see through the Earth, his ears understand the language of beast and bird, and the sense of the wind; and, through his sympathy, heaven and earth should talk with him. But that is not our science."

Why not? It can be. Science is not something outside, immobile, inert, inexorable. It is man's work. Indeed we may personify it and identify it directly with ourselves, for science is man abroad in his Universe, adventuring, prospecting, discovering, seeking truth. The motive of natural science is, literally, the extension of man into all realms, his conquest of nature's secrets, his harnessing of nature's forces—including the secrets and forces of life, consciousness, and thought which dwell in man himself.

Inevitably the accelerating consequences of scientific discovery will force men of all nations to recognize the essential community of their interest in the resources of this planet. Eventually, inescapably, readjustment will come. But the adjustment can be made with fewer losses, less agony, and a minimum of confusion, in a world aware of the meaning and method of science than in one which is

impressed only by the seeming magic of its applications and their possible aid in programs of trade, war, and other predatory competitions.

The frontiers of science are man's frontiers. They are his hard-won outposts against the darkness. And that darkness, the ignorance of the mysterious universe of things which surrounds us and of the equally mysterious universe of consciousness which pervades us, is the enemy, the only ultimate enemy. Slowly—sometimes, it has seemed, crawling inch by inch—man has penetrated the darkness to capture and control forces of gravitation, steam, electricity, to wrest the secrets of the microscopic bacillus, to blot out diseases that his father debited to the discipline of an omnipotent providence, to probe the hidden springs of life, bend protoplasm to produce new fruits of the soil to his taste, remold the very animals better to his heart's desire, and erase forever the necessity of famine. Onward, ever onward, and faster! faster the advance continues in our time. Deeper into the atom, farther into the living cell, ever more boldly reaching out into the distant realm of the dim nebulae, pushes Promethean man—reconciled to no permanent boundaries, willing to accept no limitation on the method of try-and-see-and-try-again.

It is of such trials and glimpses, of methods of seeing, and of the findings that now and then reward the seeker, that the following chapters tell. Of necessity their stories must be fragmentary, incomplete; for bulletins from the front can be only progress reports, and tomorrow's engagements may carry the outposts farther or perhaps push them back a bit for a reconsolidation of the line. Five years from now, perhaps one year from now, it may be necessary to reappraise the evidence and revise the story. But for the present, here is a picture of man embattled against certain unknowns of his Universe, with such personal touches, biographical details, and laboratory asides as it has seemed illuminating to include. In some of the chapters, where

opportunity offered to do so without overbalancing our thesis, I have made mention of applications of the new knowledge—events in science comparable to that of the occupation and settlement of new lands.

But primarily it is borderlands that we are surveying. There are several respects in which these new discoveries of the laboratories and observatories conform to this description. Obviously they are borderlands of the known, representative tracts, as we have said, of the new fronts of knowledge. Then too, these new fields of science are borderlands of the sciences. In these realms astronomy merges into physics, biology shares with chemistry, and although the techniques become ever more specialized, their uses spread into many fields. A mathematician explores the possibilities of the origin of life; a biologist's concept of organism becomes useful to the physicist's explanation of atomic behavior; an acoustician finds sound waves contributing new knowledge of chemistry; an electrical researcher, exploring the interior of incandescent lamp bulbs, is led to discoveries of surface phenomena which throw new light on the strange ways of living cells. Boundaries lose their meaning in these shifting vistas of the scientific front. It is too early to stake out claims. The only dividing line is the shadowy curve of the horizon, misty and dim in the twilight, but already brightening with the promise of a rising sun.

Chapter I · NEW HORIZONS

yearning in desire
To follow knowledge like a sinking star,
Beyond the utmost bound of human thought.
ALFRED TENNYSON, ULYSSES

LATE in the 1920's a young European arrived in the United States from Brazil. He had crossed equatorial South America by a daring short cut, climbing the Andes from the Pacific by mule, then coasting the rivers by boat to the Atlantic. Prior to that he had spent two years in the Arctic, drifting across the polar sea, enlivening the long monotony with observations of magnetism, aurorae, and other natural phenomena. Excitement was in his blood, but geographical exploration had lost its tang, and he craved new and challenging experiences. He found them in a research laboratory in Washington where he became one of a crew of adventurous physicists prospecting "the genuinely new regions inside the atom."

Passage to more than India—
Passage to you,
To mastership of you,
Ye strangling problems.

In Pasadena there is an air of expectancy as a group of technicians uncrate the steel casing which protected the precious 200-inch telescope glass on its journey from the factory in the East, where it was cast, to the machine shop

in California, where it will be ground to its designed concavity. Among them works a veteran, a self-taught optical expert who was one of Anthony Fiala's right-hand men in his ill-fated dash for the North Pole. This ex-explorer will have an important part in the shaping, testing, and installing of the great telescope—whose production is in itself one of the major scientific experiments of modern times—and here again we have the spectacle of a laboratory and its methodical regime serving as the successful antidote for Arctic fever.

In New York an aviator, home from flights to far countries, turned to a biological laboratory. He found it not only a refuge from the wearying adulation of crowds and the annoyance of an obnoxious publicity, but also a field for his talents, another means of trial of his ingenuity and patience, a new and fascinating battleground of the unknown.

The frontier is gone, say geographers—the pioneer is extinct, say historians—opportunity is no more, say economists. Yes, as Kipling anticipated them many years ago:

> Romance is dead—and all unseen
> Romance brought up the 9:15.

The borderlands today stretch along a front vaster than the terra incognita of the ancients. The pioneering is more fundamentally daring, the opportunities richer and more alluring, than anything the forty-niners knew. The frontiers are of a different kind, to be sure, and not so obvious; the pioneering calls more for brains, and for brains of a certain type, than for brawn or physical endurance; and mere squatters will not get very far with the sort of opportunities the laboratories are opening up. New laws, new disciplines, and new techniques are in the making and in the testing, and will fundamentally affect our lives, for the future of

civilization is very likely wrapped up in the future of science.

The future of science does not mean the future of gadgets—though the gadgets will come, for better or for worse, you can bank on that. The phrase refers more nearly to the fundamental knowledge out of which gadgets grow. The future of exact thinking, of the search for correct ideas about the Universe, of the quest for the central force which alike swings the Sun in its orbit among the stars and energizes the invisible mite of protein into its mechanism of life: our frontiers lie in those directions. "Pure science," some call it, but the trite term is not descriptive. Pride in the noncommercial pursuits of our pioneering professors may be arrogance, and in any event is conventional. What concerns us here is the fundamental nature of the problems which engage their attention, the value of the new knowledge as bedrock material.

Outsiders sometimes are tempted to dismiss the fundamental laboratory experiments as "technical stuff." But beware! These minutiae are the very stuff of our most practical dreams—the rich loam out of which have sprung such utilities as bacteriology, immunology, endocrinology, anesthetics, modern surgery, the electrical industry, telephone, radio, automobile, and the comforts and many of the taken-for-granted conveniences of civilized living. And future harvests must look to further extensions of the frontiers where this virgin soil is to be found.

There were, no doubt, many practical men of the seventeenth century who dismissed Isaac Newton's mathematizing as too abstract, too remote from everyday affairs. Voltaire reports that 40 years after the publication of his theory of gravitation Newton did not have more than twenty followers in England. Many professors preferred to teach the more common-sense and picturable system of Descartes. But the adventurous mathematics of Newton changed their world, his discoveries brought to pass our

world, and out of the experiments and theorizing now in course will come the new world of the twenty-first century.

In the history of science, as in that of nations, are epochs and cycles. There are periods of plodding, periods of meteoric advance, periods of pause and consolidation. Today we are in the current of a very rapid advance. And although no mind is wise enough and no imagination penetrating enough to stake out the limits of discovery, we are capable of glimpses of our borderlands. The present seems a propitious time for a glance backward, to see by what trails we have come, and for a general survey of existing frontiers, to see where we stand in relation to the great unknowns of nature.

I

At the turn of the century, the fundamental physical science found itself in the surge of a great excitement. Only 5 years before, in 1895, William James had heard a Harvard professor say that all the fundamental conceptions of scientific truth had been found and only details remained to be filled in. Nor was this complacency peculiarly local. The English historian Gerald Brown was writing: "The great things are discovered. For us there remains little but the working out of details." And in Leipzig the chemist William Ostwald was expressing the same idea.

Before the end of that year, 1895, one of Ostwald's German colleagues chanced upon a strange influence radiating from the sides of an activated vacuum tube. It was Röntgen's discovery of x-rays. The curious behavior of these rays prompted Becquerel in France to make certain experiments with uranium which in 1896 gave the first glimpse of radioactivity. In 1897 J. J. Thomson in England discovered the electron. And 1898 brought forth, from the Curies' brilliant searches, radium.

Four supreme discoveries in 4 years! No wonder the twentieth century opened in an atmosphere of expectancy.

This sudden upturning of strange phenomena, opening new vistas and posing startling new questions in the moribund realm of physics, had repercussions in all the sciences—quickening hopes, spurring endeavors, suggesting fresh trails to be blazed by experiment.

And it suggested, too, the importance of research to many a thoughtful layman, including, fortunately, some men of large means. It seems significant that at about the time of Röntgen's researches, Alfred Nobel decided to set apart his great fortune as an endowment to provide annual awards for the encouragement and rewarding of scientific discovery and other praiseworthy human pursuits.

In 1902 Andrew Carnegie established the Carnegie Institution of Washington, and today its Mount Wilson Observatory, Geophysical Laboratory, Department of Research in Terrestrial Magnetism, Department of Genetics, and a dozen other experiment stations are among the most active outposts of the scientific advance.

Also in 1902 the Rockefeller Institute for Medical Research was established in New York. The quality of its work and the caliber of its contributions are indicated by the fact that twice has a Nobel prize come to members of its staff.

These establishments are representative of scores of institutions in Europe and America, with a scattering few in Asia, that have been set up within the last 37 years—some of them privately endowed, some state foundations, some attached to universities. They are our advance stations, observation towers, peepholes on the unknown. How far we penetrate the surrounding mysteries depends on the reach of our instruments.

Consider, for example, our awareness of cosmic rays—those strange bombardments from outer space. No one can see a cosmic ray, no one can feel it. The thing was stumbled upon in the early 1900's through the curious fact that electrically charged bodies inevitably lost their charges, an

effect that could be accounted for by the influence of invisible rays. But what kind of rays? Physicists competed in attempts to trap the suspects. Year after year they increased the sensitivity of their detectors, adding some refinement, some increased delicacy, progressively getting better results, until at last in 1929 the Russian physicist Skobelzyn succeeded in photographing the evidence of a cosmic ray. His camera snapped for a fraction of a second the track made by an atomic fragment that had been smashed out of matter by the collision of a cosmic ray.

Now the probability of a ray hitting an atom and fragmenting it is very small. In the air, where the first detections were made, it is reckoned that the odds per second are about one or two to ten million million million. Out of every ten million million million molecules, one or two may get hit. The encounter seems exceedingly improbable—billions of times less probable than the occurrence of such rare human events as the birth of quintuplets. To have contrived an instrument sensitive to these rarities and capable of recording them in terms of physical measurement is evidence of the resourcefulness of our cosmic explorers.

Equally amazing instrumental advances are to be noted among other techniques. The biologist works with a microdissecting apparatus attached to his microscope and is able to perform a deft surgery on single cells. The reach of the microscope has been extended by the use of new illuminants; fluorescence activated by ultra-violet radiation is showing details beyond the reach of the visible rays. Recent improvements in photographic speed are being employed by the cytologist to get microscopic motion pictures of that world of perpetually changing form which lies in protoplasm.

Meanwhile, astronomy has extended its grasp to distances unimaginable. In 1905 the whole universe of stars was believed to be contained within the Milky Way, whose

diameter was reckoned as about 7000 light-years. Today our measurements indicate that the Milky Way has a diameter of about 100,000 light-years. But large as it is, we now know that it is far from comprehending the whole population of stars, that it is only one galaxy among millions of others. Recently, at Mount Wilson Observatory, Edwin Hubble photographed one of these outside systems at a distance estimated to be 500 million light-years.

Thus does our reach progressively extend and the horizons recede with the increasing sensitivity of the instruments through which we prospect the borderlands.

2

The borderlands are as many, almost, as the specialists who are exploring them, but perhaps we can focus our seeing on a few and get some impression of their extent by considering some of the primary problems on which science is now engaged. P. A. M. Dirac, successor in the professorship once occupied by Sir Isaac Newton at Cambridge University, has listed three fundamental problems as awaiting solution:

1. The relativistic formulation of quantum theory.
2. The nature of the atomic nucleus.
3. The nature of life.

The first two of these problems were unknown at the turn of our century, for the theory of relativity was yet to be born, the idea of the quantum had just arrived, and the existence of the atomic nucleus as we know it was not even suspected. But the problem of life's mechanism, which Professor Dirac qualifies as "more difficult," has been with us since the earliest days of science. Indeed, it is the problem of problems, the most intimately personal and, for human beings, the most important.

Machines have been made to simulate certain processes of life. Chemists and engineers have even designed mechanisms which provide crude analogues of mental activity—

machines that learn, forget, and remember. Other chemists have succeeded in crystallizing a heavy protein out of a solution made from living matter—a substance which under certain conditions behaves as an inert chemical and under other conditions multiplies and reproduces itself somewhat like a living species.

While biochemists and biologists are attacking the problem by methods of their specialized techniques, Professor Dirac suggests that the secret of the living mechanism is also a fit subject for the physicist to explore. Vitalists scoff at the proposal. But on the other side it is reasoned that life is wholly dependent on matter, that matter behaves at times as if it were a structure of electrically charged entities, therefore that life is basically a field for the physical scientist.

3

If the physicist eventually is to unravel the mystery of life, perhaps it will be only by solving the more fundamental mystery of matter—and this is the theme of the second item on Professor Dirac's list. Of all the frontiers inviting the physical scientist today, the atomic nucleus is the most tempting, and it is the one that is receiving the most attention. When Sir Herbert Austin, out of his motor profits, presented the Cavendish Laboratory at Cambridge with a generous purse in 1936, the director, Lord Rutherford, announced that the first use of the money would be to provide high-voltage apparatus for studies of the nucleus. In America, where many of the new types of atom-smashing machines were invented, there is a veritable race for high-powered armament. At least a dozen laboratories are now armed, or in process of arming, in this intensifying campaign against the invisible citadel of physical reality—the atomic nucleus.

Our present knowledge of the nucleus may be likened to our knowledge of the atom in 1912. At that time we knew

that the atom consisted of a central massive core and encircling electrons. Today we know that the core is a complex structure or aggregate of different parts, or at least we know that we are able to smash different things out.

Prior to 1931 it was believed that these interior parts were of two kinds only: lightweight negatively charged *electrons*, and heavyweight positively charged *protons*. But around Thanksgiving Day in 1931, at Columbia University, Harold C. Urey discovered a hydrogen atom of double-weight nucleus—a thing so strange that it suggested a new element, almost. Urey named it "deuterium." Just as Röntgen's x-rays were the opening shot of the revolutionary decade of 40 years ago, so Urey's deuterium was the beginning of the breath-taking succession of atomic finds of today.

Early in 1932, only a few weeks after Urey had made his discovery in New York, James Chadwick was experimenting at the Cavendish Laboratory in Cambridge to test a peculiar effect that had been sighted by investigators on the Continent. They had misunderstood the effect and misinterpreted its cause, but Chadwick now recognized the phenomenon for what it was and attributed it to the presence of an unknown particle. The new particle was massive, like the proton, but unlike the proton it carried no electric charge, it was neutral, therefore Chadwick named it *neutron*. The neutron helped to explain Urey's deuterium,—for was not that heavyweight hydrogen nucleus simply a proton and a neutron interlocked? This seemed a reasonable explanation of the double weight, and is still the accepted idea.

Later in that same 1932, by a brilliant stroke at the California Institute of Technology in Pasadena, Carl D. Anderson detected the presence of another particle apparently coming out of the nucleus—a lightweight positively charged something which he named *positron*.

A year following, at the Radium Institute in Paris, the Joliot-Curies were exploring the metal boron by bombarding it with alpha particles, when accidentally they discovered that the boron had become radioactive in somewhat the manner of radium. It was firing back, out of its invisible nucleus. And its projectiles turned out to be Anderson's positrons. Since then more than sixty other familiar elements have been bombarded in turn, and each has been converted into a furious geyser of energy, discharging positrons, electrons, and even gamma rays comparable to those emitted by radium.

Do you wonder that the nuclear explorers are excited? Anderson did not get to sleep the night after he discovered the positron. Sitting one day in the office of another atom chaser, I picked up a book from his desk, and, opening it at the flyleaf, chanced to read a hastily scribbled date and a jubilant memorandum: "Proton tracks today!"

There is endless fascination here, the everlasting whisper of the unknown, the tantalizing call of the hidden but not unattainable reality—"Proton tracks today!"

4

Perhaps in the nucleus will be found the answer to that other problem in Dr. Dirac's list—the reconciliation of relativity and quantum theories. The task here is more recondite than the others, but no less fundamental to the integrity of our knowledge.

The theory of relativity dates from 1905, its generalization from 1915, and today it is basic in the scientific interpretation of celestial mechanics and other phenomena involving large bodies, vast distances, and high velocities.

The theory of the quantum, first introduced in 1900 to explain certain strangenesses in the behavior of radiation, was applied to the atom in 1913, and extended and formalized into more satisfactory theories of atomic mechanics

in 1926 and the years immediately following. We may say that, as relativity best accounts for the large-scale phenomena of stars and planets, quantum theory best accounts for the small-scale phenomena of atoms and electrons.

But between the two theories are discrepancies, or at least restrictions. The more glaring of these are, paradoxically, too subtile for brief and simple exposition, but perhaps we may glimpse the nature of the dilemma from the following comparison.

In relativity theory the physical reality is described in terms of the familiar three dimensions of space and one dimension of time, so that at a given moment each star, each planet, and even each particle has a certain position and direction with reference to other stars, planets, and particles. Each object is said to describe a "world line" as it courses its way through the Universe, traveling a track ordained for it by the curvature of space, which curvature in turn is ordained by the masses of the bodies which inhabit space.

In quantum theory the case is quite different. Here the dominating law appears to be the uncertainty principle which says that exact position and precise velocity cannot be measured, and therefore are not known to exist. Thus, the space-time definition of events becomes indefinite. Indeed, in the quantum concept, as F. A. Lindemann of Oxford points out, "We must conclude that there are no such things as world lines. As a first approximation they would be represented as world tubes. The tubes must not be thought of as having rigid boundaries, but rather as shading off from the center outward according to a form of error law."

There are certain relativity effects which have been found to operate in the atom, first pointed out by Arnold Sommerfeld some years ago, and Dirac himself is the author of a number of interesting developments of theory combining ideas of relativity with those of quantum

mechanics. But the consolidation of relativity theory with quantum theory, or the discovery of the unified system which includes them both, is yet to be attained. Recent projects in this direction have been essayed by Albert Einstein, Arthur S. Eddington, and George D. Birkhoff. So the riddle is not rusting. All these approaches are significant and helpful, but the difficulties still are very real, and the problem remains one of the most formidable frontiers of science. It will continue to be an inviting field for exploration so long as there are those who believe that nature is coherent, orderly, and subject in all its members to law.

5

The approach to problems of science—those of astronomy, physics, chemistry, biology, and all the rest—is limited by the conditions of man's environment. It is granted that creatures living at the bottom of the sea, where no visible rays ever penetrate, and where the surrounding medium is a dense liquid, would have a different impression of the cosmos and therefore a different cosmology from creatures living as the human race does at the bottom of an ocean of air. A scientist on the planet Venus, which is always swathed in dense clouds and from whose surface no image of Sun or other star is visible, would picture the firmament quite differently from an observer on the arid surface of Mercury, on whose cloudless horizon the Sun never sets; and still different would be the outlook of an investigator resident on the giant Jupiter, with its surface still plastic and its atmosphere impregnated with ammonia gas and methane. Nor is it only the view upward to the skies that is colored and transfigured by these planetary differences, but also the outlook downward to the planets themselves, to their surface features: the solids and liquids, polar zones, equatorial belts, and the thin films of

life that may (or may not) overlay certain favorable surface areas of these spinning orbs.

The specter of life haunts all human hypotheses about the other planets, and doubtless it will continue to plague our conjecturing until the first rocket ship makes a successful landing abroad and is able to send back a message of its discoveries. Our speculation of life in other worlds is not unnatural. Man is lonely in his new-found Universe, this deepening shadow of space-time, and seeing "other little ships" cannot but wonder "whether in yonder spheres there is also an Above and a Below," the living and the not-living. Life on the Earth ranges from the invisible microbe, which can endure both boiling water and liquid air, to man, who cannot long survive so much as a 1 per cent change in his body temperature. With the demonstrated existence of this wide range of protoplasmic sensitivity on the Earth, who can deny that life of some kind may be possible on hot Mercury or cold Pluto or in any of the planetary arrangements between these two extremes? Human life, no; or hardly; for it is conditioned on a finely balanced internal environment which in turn is dependent on a certain balance of external forces: the solar constant of radiation, the atmospheric constant of oxygen, the presence of water and other minerals—a combination that exists perhaps nowhere in the Solar System but on Planet 3. But it is not impossible that the resonance phenomena which we call life may assume other forms, given other environmental conditions. The probability of life existing on other planets, or, as Sir Francis Younghusband would have it, on or in the stars, reduces to a definition of what life is. The living unit, as we shall see in a later chapter, is exceedingly difficult to define.

Our knowledge of nature is limited by our ability to apprehend the materials and the forces which meet us—both those of the Earth, which we encounter in their hurryings to and fro, and those of the Universe outside,

which beat upon us from the stars and the darkness beyond the stars. Nor is it only our five senses that limit the boundaries of the known. Ingenious man has devised apparatus for translating the invisible, the inaudible, and the imponderable into a code intelligible to human sense organs. By means of lenses, mirrors, prisms, magnets, fluorescent salts, electrically sensitive filaments, photographic plates, and other extensions of eyes, ears, and fingers, scientific man has discovered much that to the unaided senses is nonexistent. The story of modern discovery is very largely a story of increasing ingenuity of instruments.

But the reach of our instruments, and indeed the very biological nature of our observers, is conditioned, as we have said, by the nature of the observation post from which we view our world. The rotating, revolving Earth is subject to certain restrictions imposed by its mass, its distance from the Sun, its motions, the constitution of its enveloping atmosphere, and the perpetual panorama of change which attends its flight through space. Our observation post is not constant. It is not the poet's

> round and delicious globe,
> moving so exactly in its orbit forever and ever,
> without one jolt or the untruth of a single second.

On the contrary, it is a quite bulgy, irregular, tempest-tossed spherule of air, as well as a globe of land and sea. And what we glimpse, and how we interpret our snatches of the unknown, depends very directly on these terrestrial conditions. Therefore we begin our quest of the borderlands with a look at our observation post—our little ship plowing its trackless world line among the stars.

Chapter II · FRONTIERS OF EARTH

The Earth never tires,
The Earth is rude, silent, incomprehensible at first,
Nature is rude, silent, incomprehensible at first;
Be not discouraged, keep on, there are divine things
well envelop'd,
I swear to you there are divine things more beautiful
than words can tell.

—WALT WHITMAN, SONG OF THE OPEN ROAD

THE terrestrial reality indeed is "well envelop'd." A star is obvious, the simplest thing in nature Eddington has called it, a globe of gas implicitly obeying the gas laws. And since we know the gaseous state of matter better than we know the liquid or solid state, it follows that we can know stars better than planets simply because stars are made of the stuff with which we are most familiar. A star is a glowing system, self-revealing, self-advertising—a vast aggregate of matter in a primitive state of motion, fragmentation, and organization, which ceaselessly broadcasts the most intimate news of itself. But a planet, the cooled fragment of star stuff—that is something different.

The planet broadcasts no radiation of its own that we can discern at a distance; it only gives back the reflected rays of the Sun which warm and illumine it. The planet hides its internal nature within a crust of rocks and metals, and

complicates our seeing the solid phases of its continents and islands and the liquid phases of its seas by an enveloping gaseous phase of atmosphere. There is nothing perceptibly energizing, or generative, in its behavior. It is a dependent body, subservient, inert. William Bolitho, in one of his essays, described the human race as "blood clots on a clod." His picture is obviously incomplete and superficial—for great and "well envelop'd" is the might of hemoglobin—but I suppose most of us who wince at being called blood clots would readily agree that the Earth is a clod. The Earth never tires because it has no capacity for fatigue. It is brute matter, clay. And while the majesty of man and all his company of conscious creatures has arisen from this terrestrial compost, that only lends the more dignity to man, elevating him the higher by contrast with the lowly dust of his origin. So we celebrate, in our moments of inspiration and emotion, our testament of faith in the inerrant course of evolution, forgetting or ignoring the testament of fossils—the mute evidence of species that also once flourished and proliferated but perished aeons ago under the scourging changes of this spinning clod that eternally calls the tune for our dance of life.

Perhaps the Earth is a clod, but if so it is a vibrant clod, responsive to an endless symphony—or cacophony—of cosmic influences. In truth, so sensitive is the planet to its environment, that one might accurately liken our "round and delicious globe" to a tuning fork, or to a delicately poised magnetic needle, or to one of those highly vibrant quartz crystals used to detect frequencies beyond the range of audibility. In the vast span of the Universe our dwelling place is relatively a point, smaller in the scale of the whole than a pollen grain is in the scale of the Solar System. And yet, it is this minute point that picks out of space the energy that drives our terrestrial machine—its flow of winds and of water, its growth of living things, its invisible pulses of electricity and magnetism.

I

If you look at the planet Mars, a small bright red spot in the night sky, you see an object that is considerably nearer the Earth than the Earth is to the Sun. To an observer on the Sun, the Earth would appear not much larger than Mars appears to us. Imagine, then, such an observer peering out through the thin solar corona into the surrounding void and seeing these dots of borrowed light: Earth, Mars, Jupiter, and the others. It would seem a slight probability that any object so small, covering so diminutive an area of the sky, would be able to capture any considerable portion of the energy flooding space. The answer is, of course, that it can capture only so much as its surface intercepts—and this suggests two actualities: first, the tremendous volume of energy poured out by the stars; and second, the sensitivity of our planet to these influences.

Our nearest star is the master influence, so far as knowledge goes. Whether or not the Earth owes its origin to the Sun is an unsolved problem. One recently proposed hypothesis inclines to the belief that both Sun and planets emerged simultaneously from some cosmic event of a few thousand million years ago. But this is only one of many surmises. Whatever the planetary genesis may have been, there is no question that the Earth's destiny is inexorably bound up with the Sun's, and that our planet owes much of the present form of its surface features to solar radiation. The torrent of outgoing energy totals five hundred million million million horsepower continuously, and the Earth's surface is sufficient to intercept only the two thousand-millionth part of this—a quota that averages about one horsepower to each square yard of the sunlit Earth. Only a small fraction of this horsepower is absorbed and put to work, but that is quite enough to keep oceans liquid and atmosphere gaseous, to generate our weather, and in these and other ways to mold and remold the fabric of our planet.

The Moon is a far lesser mass. Its weight is only the twenty-seven millionth part of the weight of the Sun, but the Moon is four hundred times nearer than the Sun, and it makes up in proximity for its bantam weight. The tides of our seas are largely an effect of the gravitational influence of the Moon. Less known is the fact that the lunar gravitation lifts a tidal wave of air which heaves along the upper surface of our atmosphere and also a lesser tide down in the rocky crust of the Earth.

Several evidences of this crustal tide have been offered. Alfred L. Loomis and Harlan T. Stetson report that when the Moon is passing over the North Atlantic Ocean, the city of Washington is a few feet nearer London than it is at other times. Total differences sometimes amount to as much as 60 feet. The change in the variation seems to follow the Earth's seasons, indicating that solar influences also may enter into the situation. Such part of the shift as keeps step with the Moon's position suggests that our satellite through its gravitational influence causes the rocky layer beneath the sea to rise and by virtue of that movement to shorten the distance between our continent and England. Recently scientists at a Chinese observatory compared the time signals between Shanghai and Berlin and found a difference of 60 feet in the distance between these two cities, a shift apparently related to the position of the Moon. In Pittsburgh, P. D. Foote used a delicate gravitational instrument which detects minute differences in the distance to the center of the Earth. Dr. Foote found that when the Moon was at its zenith over Pittsburgh the crust of the Earth apparently rose, and when it was on the opposite side of the Earth the crust fell, the difference being about twenty-three inches. All these reports must be disquieting to astronomers and other surveyors, accustomed to determining the latitude and longitude of their observatories, and proceeding to work on the assumption that the places are fixtures. A difference of mere feet

between America and Europe is not enough to affect steamship fares or cable tolls, but it is enormous to those who must measure longitude, reckon time in split seconds, and determine star positions within hair's breadths. Stetson has also compared the dates of earthquakes with the lunar calendar, and reports that the quakes are most frequent when our satellite is in such positions as to exert its maximum tidal forces.

Smaller, numerous, and with effects different from that of the Moon are the meteors. They come closer and actually add themselves to our mass. Estimates based on counts made in different parts of the Earth show that approximately one hundred thousand million meteors dart into our atmosphere every twenty-four hours. Most of them are mere granules of dust, motes from interplanetary space, and are consumed in the upper air; but some are huge chunks and, despite the terrific heating engendered by their swift flights and friction with air molecules, may finally reach the surface of the Earth as solid bodies. The largest known is the great Ahmighito meteorite, a part of the exhibit at the Hayden Planetarium in New York, a roughly triangular lump of iron-nickel which weighs more than 36 tons. It was found in Greenland, and brought to New York by Admiral Peary. There are a few others in our museums that weigh tons, but most of the ten or eleven thousand meteorites that have been recovered weigh only pounds or fractions thereof. Doubtless innumerable millions lie buried in oceans and waste lands. F. G. Watson and J. L. Greenstein, of the Harvard College Observatory, recently made a study of this continual rain of "shooting stars," and they reckon that the mass of the Earth is increased about 3½ tons annually by these additions. This yearly accretion is negligible in proportion to the total mass of the Earth: 6570 million million million tons, according to the determination of Paul R. Heyl, made at the Bureau of Standards in Washington. Meanwhile it

may be that we are losing as much or possibly even more through the escape of light gases from our atmosphere and through the disintegration of matter by radioactivity or other forces of transmutation.

Meteors seem to have another terrestrial influence. It is possible that they contribute to the ionization or electrification of the upper air. The probable reality of such an effect is suggested by the behavior of radio signals; these seem to increase their strength at times of meteoric showers. As a meteor plunges into the atmosphere from interplanetary space, traveling at speeds which range from 10 to 100 miles a second, it is heated to incandescence by the impact and friction of air particles. Temperatures of 3000° to 7000°F. are generated, intense darts of ultra-violet light are released, and some of these may collide with air molecules and smash them. Thus the meteor, as it plows through the atmosphere, leaves a trail of mutilation in its wake. There have been instances in which a radio investigator saw a meteor shoot across the sky at the moment when he was making a test, and the sudden increase of static in the earphones was unmistakable.

But these things that the eye sees—the Sun, the Moon, and the darting meteors—are only the obvious among the influences that ring their changes on our vibrant Earth. There are also more hidden bombardments—cosmic rays, for example. Although they are invisible and imperceptible to any human sense organ, cosmic rays have disclosed themselves as the superlative energy carriers of the world. An electron in a thunderbolt may move with a pressure of 1000 million volts, but some of the electrons knocked out of matter by cosmic rays exhibit energies of 20,000 million volts—and even more, according to certain estimates.

It seems improbable that the Earth could be under continuous battering by such forces without being affected, and many have been the speculations on the nature of the effects. Several years ago John Joly, of Dublin University,

suggested that the incidence of cancer on the Earth might bear some relationship to cosmic radiation. It remains a provocative idea, without proof.

Later, when H. J. Muller at the University of Texas discovered that the genetic patterns of living creatures can be changed by x-ray bombardment, causing the descendants of the radiated individuals to develop new physical characteristics, the idea was proposed that cosmic radiation might be continuously acting in this same way in nature, and thus furnish the key to organic evolution. This hypothesis, born of experiment, is entirely reasonable. And while it appears on statistical grounds that the density of cosmic rays (the number of rays falling on each square yard of the Earth's surface per second) is not sufficient to account for all the mutations occurring in nature, there is no reason to doubt that some of them are attributable to this source.

2

Since the outer frontiers of the Earth lie in its atmosphere, one would naturally expect that any effects of outside influences would show themselves there first. Such is the case, though we are still fumbling for exact knowledge. Much has been discovered with the aid of radio. In truth, the capital achievement of modern terrestrial exploration is the radio discovery of the electrical structure of the atmosphere.

It is not obvious that our atmosphere is an electrical ceiling, with an electrical roof above the ceiling. The old idea pictured a halo of gas surrounding the more solid globe, and presumably the gas thinned to the vanishing point a hundred miles or so above sea level.

When Hertz discovered radio in the 1880's, and inventors began to speculate on the possibilities of wireless communication, it was assumed that such communication could connect only relatively near points on the Earth's surface. Radio waves are undulations in space rather than

in air; therefore the waves could not be expected to conform to the spherical contour of the atmosphere. They would go out from the broadcasting antenna in all directions, like the upper half of an expanding bubble, but they could not bend round the planet's curve. Light did not bend round that curve, and radio was a species of light. The only way the theorists saw to bridge distance by wireless was to build very tall transmitting and receiving antennae. As with a lighthouse so with an antenna: the higher it was, the more distant its horizon.

Marconi's early experiments gave strength to this supposition. On Salisbury Plain, England, in 1896, he transmitted signals over 2 miles. In a few months, with taller antennae and more powerful apparatus, he had doubled this distance; and so progressively as he improved his instruments and increased the height of his antenna, he increased his range. By 1900 he was spanning 60 miles with ease, and occasionally, under favorable conditions, picked up a message at 100 miles. Early in 1901 two of his stations 186 miles apart were clicking off messages to each other. Every gain whetted his appetite for more distance, and in the summer of 1901 he set himself an audacious test. He would build a yet more powerful transmitter and install it with a yet more lofty antenna on the Cornish coast. Then he would cross to America and listen for its signals.

Marconi shared the secret plan with only a few intimates whose cooperation was necessary. Others thought he was embarking for more of his ship-to-shore experiments when he sailed in late November. He landed in Newfoundland without publicity. The rest is history. On December 12, while his men struggled with an enormous kite to support the slender wire aerial above the windswept coast, Marconi sat alone in a barracks-like room of the hospital with a pair of headphones clamped over his ears. For an hour he waited, like a man in a waxworks, motionless, tense, listening. At half-past twelve, noon, a faint staccato quivered in the

phones—the three short dots of the letter *s* repeated over and over again. It was the prearranged signal. He called his men. Nervously, almost violently, he handed the phones to one of them, saying, "Can you hear anything?" The instrument was passed to the next man, and to the next. Each in turn heard the feeble click of the code, "zip-zip-zip." Wireless power had swung its mysterious resonance across the Western Ocean to be heard by a human ear for the first time.

How had it done this? asked Lord Rayleigh. The waves could not travel through the Earth; how could they curve round it?

Almost immediately the right explanation was suggested. If the waves could not bend of their own accord, perhaps they might be bent by some outside agency. It was known that an electrical conductor, a sheet of copper or a wire screen, for example, would reflect radio waves in the laboratory. Assume such a conductor in the upper air. A layer of ions (mutilated air particles) would serve the purpose quite as effectively as a metal screen. If there existed this ionized sphere of electrification high above the Earth's surface, the long-distance transmission of radio waves could be explained. It could be explained as a consequence of a mirror effect. The waves striking the concave undersurface of this layer of ions would be reflected back at the same angle with which they struck it and on reaching the ground would be reflected upward at a similar angle. And so, alternately bouncing the ceiling and the ground, they would zigzag round the globe as far as their strength carried.

Such, in brief, was the theory proposed by two electrical engineers, Oliver Heaviside in England and A. E. Kennelly in the United States. The idea of an ionized upper region was not new. It had been suggested some years before by the British magnetician Balfour Stewart on other evidence. But Kennelly and Heaviside were the first to apply it to

explanation of radio transmission. The explanation remained merely a hypothesis for more than twenty years. Finally, in 1925, its truth was established independently by three convincing experiments.

At the laboratory in Washington of the Carnegie Institution's Department of Research in Terrestrial Magnetism, Gregory Breit and M. A. Tuve directed a radio impulse straight up, and in a fraction of a second the echo came bounding back—clear evidence of the existence of some sort of electrical mirror.

At the Naval Research Laboratory near Washington, A. H. Taylor and E. O. Hulburt sent up a series of short-wave impulses at an angle, and measured the skip distance to the first ground reflection of the wave—another bit of testimony from the upper-air reflector.

And in England, near London, W. A. Appleton and M. A. F. Barnett reached up and touched the invisible by still another method. They radioed signals of different wave lengths, and, by measuring the patterns of interferences which resulted when the returning waves bashed into the outgoing waves, they were able to demonstrate the presence of the reflector and to gauge its height.

Thus the Kennelly-Heaviside Layer, the ionosphere, took its place on the chart of the planet Earth as a known but as yet unexplored borderland.

Perpendicular exploration has advanced swiftly since then. While Byrd and Ellsworth were edging perilously into unknown stretches of Antarctica, adding new mountain chains and plateaus and other features to the surface map of the Earth, these radio explorers, comfortably seated in their laboratories in Washington, London, and other congenial bases, have been pushing steadily into the ionosphere. They have discovered lofty mountains, wide plateaus, sometimes sagging valleys in this ever-changing realm of the upper air. The aerial mountains, valleys, and plateaus never stay put, but forever are shifting their

positions and altering their dimensions under the pressure of sunlight, the heat and electrolysis of the solar rays, and other causes.

The varied influences produce a varied structure whose complicated pattern we are just now in process of disentangling. Indeed, we may liken the ionosphere to a section of a geological stratification, with one sky land piled on another, each continually changing its density, its thickness, and perhaps its topographical features. The whole subject is very much "up in the air" at present, but this much we know.

If you send out a radio signal of long wave length, such as is used by the general broadcasting stations, the reflections come from a height of about 70 miles. But if your impulse is of short waves, such as were used to communicate with Admiral Byrd in Little America and such as are commonly used for transoceanic broadcasts, the reflections will be longer and the distance between reflections will be greater, indicating that the height of the mirror is from 115 to 150 miles. These levels vary from season to season, from hour to hour at times, and are different for different latitudes; but the two sharply distinguished regions are discernible at all hours and from every part of the Earth's surface, and therefore appear to be permanent features. The Kennelly-Heaviside Layer thus turns out to be two layers: the lower, or *E* layer, serving to reflect long radio waves, and the upper, or *F* layer, being a reflector for shorter waves to which the lower layer is transparent.

The discovery that some wave lengths are reflected from a lower level than other wave lengths provides the radio explorer with a master tool—a combination hand and eye which can reach into the ionosphere and spy out the hidden lands. By starting a transmission at one wave length and gradually changing the signal to shorter and yet shorter waves, one may discover the critical wave length at which the pounding of the invisible vibrations

against the invisible barrier becomes sharp enough to pierce through the Earth's ceiling, the *E* layer, and strike the Earth's roof, or *F* layer. This type of investigation was pursued at the National Bureau of Standards by a trio of researchers—S. S. Kirby, L. V. Berkner, and D. M. Stuart —with the result that they discovered still another sky land. It, however, is an intermittent reality, appearing during daytime and fading at night. This new-found reflector forms in the upper part of the *F* region. It begins to show its presence right after dawn, grows steadily in reflecting strength, reaches a maximum shortly after noon, and then begins to shrink. After sunset it has disappeared, and the *F* layer resumes its function as the radio roof. Most of the authorities regard this daylight upper region as a temporary tent over the more permanent *F* layer or roof; therefore it is called the F_2 layer, while during this double phase the original *F* layer is known as F_1.

Still more transitory atmospheric structures are reported. Sometimes the lower or *E* layer splits into two, while the *F* layer on occasions shows not only its daytime F_1 and F_2 but also an F_3. And occasionally yet another stratum appears midway between the uppermost *E* and the lowest *F*. Thus, three sporadic ledges are added to the two permanent and the one sunlit layer, making occasionally as many as six stories in our electrical superstructure, each with its individual characteristics, each a reflector of all radio waves longer than a certain critical wave length, a transparency to all waves of shorter length. No wonder radio has a temperament!

3

Although no pilot balloon, rocket, or other aerial vehicle has been able to sample the ionosphere for our benefit, it is possible by means of radio waves to sample it indirectly. We know, from laboratory tests, what a gas of a certain density will do to waves. When the gas is ionized it will

reflect radio waves of a certain wave length and pass all shorter than that wave length. Ionize the gas to a still higher state of electrification, and its opacity increases—waves that got through before are now turned back. Many experiments prove that the critical wave length is a direct index to the density of ionization. Therefore, by measuring the precise wave length at which a layer of atmosphere ceases to reflect signals and allows them to pass, our radio explorers are able to tell the state of ionization of the layer. Very exact studies of this kind have been carried on for several years at widely separated points on the Earth's surface, and we now know pretty closely the ionic density of each of the atmospheric layers and their changes. The records cover daily and seasonal changes, the progressive changes that have taken place over a period of years, and the sporadic changes that occur at irregular intervals. Since the ionization is accomplished presumably by radiation from the Sun, and since the amount of radiation reaching a given latitude of the Earth may vary from month to month with the seasons, and from year to year with the sunspot cycle of about 11½ years, these changes in the state of ionization are to be expected.

But I doubt if many users of radio have any conception of the extent of the changes that have taken place recently in these upper regions of our planet—these aerial lands of thinnest gossamer, their material more diffuse than that of the highest vacuum ever attained in a laboratory, and yet of a substantiality so real and so indispensable to the operation of long-distance radio communication that any subtraction from or addition to the density is instantly apparent. Before we look at the record of startling changes, let us get clearly in mind the general picture of what is happening up there beyond the blue stratosphere.

The Sun's radiation must travel some 93 million miles to reach the Earth. But it travels through the vacuum of interplanetary space, and in consequence of the high

transparency of its medium it strikes the upper atmosphere with an energy not much different from that with which it leaves the Sun. This means a temperature of approximately 10,000°F. Whether or not the temperature of our outermost air is 10,000° we do not know, but the point is that whatever radiation arrives carries with it the possibilities of that degree of excitation. The solar radiation is of a wide range of vibrations, including ultra-violet light, visible light, the invisible infra-red, and corpuscles or particles of exploded sun stuff.

The thin outlying fringe of the atmosphere gets the full force of this solar bombardment. Perhaps every one of its atoms that chances to get hit is violently mutilated, and so the greatest slaughter of particles takes place here. This maximum ionization forms the daylight tent which we have called the F_2 layer.

The solar radiation that survives these outer collisions passes on into deeper and denser zones of air, and its chance encounters smash other atoms here to form the stratum which we have called the F_1 layer.

Still deeper penetrates the remaining torrent of Sun rays, reaching yet denser areas of air, and performing the mutilations whose fragmented atoms constitute the still lower level, our radio ceiling, the E layer.

The sporadic intermediate layers alluded to in the preceding section are no part of the normal picture; they are supposed to be consequences of unusual eruptions from the Sun, and frequently occur at times of magnetic disturbances in the Earth and auroral displays in the skies; and to keep the present discussion simple and uncomplicated we shall ignore the exceptions here.

What we have at high noon over the city of Washington, for example, on an ordinary summer day, is this invisible structure of electrified gases: the E layer, about 70 miles overhead, with a relatively sparce population of ions; then the F_1 layer, about 115 miles from the ground, with a

higher number of ions, though the atmosphere itself is thinner here; and finally, at about 200 miles (sometimes higher), the uppermost or F_2 layer, a still finer tissue of matter but an enormously higher number of ions. The radio program that comes to you from your local broadcast station is reflected by the bottom or E layer. That which comes across the Atlantic from London may be reflected by the intermediate or F_1 layer, while messages from Antarctica or Australia are likely to use such short wave length that they penetrate both E and F_1 and are reflected only by the F_2 mirror. Since the density of its ionization determines whether a layer will pass a certain wave length or reflect it, we can be sure that any considerable change in the ionization of the upper air is bound to influence man's wireless communications.

And considerable changes have been taking place. For instance:

In the year 1934, at summer noon, in Washington, the uppermost or F_2 layer averaged 700,000 ions per unit.[1] The longest wave that was just able to penetrate this barrier was one of 40 meters wave length. Everything longer was turned back. But in 1936 the case was quite different, for by then 40-meter waves were unable to get through. The explorers, sounding that outer barrier with shorter and yet shorter waves, found that the signal must be reduced to 21 meters wave length before it could escape. There were more ions up there in 1936 than in 1934, the wave length 21 meters gave a direct clue to the ionization, and the reckoning showed the enormous average of 2,500,000 per cubic centimeter. The density had more than tripled in the 2 years!

Corresponding changes, though in lesser degree, showed in the lower layers. In 1934 the density of F_1 was 250,000, and its critical wave length 65 meters; in 1936 density

[1] Equivalent electrons per cubic centimeter.

was 350,000, and critical wave length about 57 meters. For the *E* layer, in 1934 the density was 150,000, the critical wave length 85 meters; by 1936 density had increased to 185,000, critical wave length had decreased to 77 meters.

While these striking differences were measured in the daylight conditions of 1934 and 1936, it is worth noting that a smaller change showed in the night conditions. As soon as the rotating Earth removes Washington from the field of the Sun's radiation, the mutilated particles of the upper air tend to repair their wreckage. An electron in its wanderings will encounter a broken atom that is minus an electron, and the two join to form a whole again. By this process of mutual repair the uppermost layer of ionization soon disappears or its residue merges with the intermediate region. At the same time the intermediate region and the lower region have been undergoing similar atomic restorations, and by midnight this is the state of affairs: The upper or *F* region has thinned to a density of only 100,000 ions per unit, and in consequence a 100-meter wave is able to get through it. The lower or *E* region has thinned to only 7000 ions per unit, and waves of 400 meters readily pierce its depleted screen. In citing the critical wave lengths here, as in other parts of this discussion, the values given are those for waves striking the layers at the normal angles of incidence. For reflections at other angles, other wave lengths become critical.

Despite the far greater number of mutilations occurring during the daylight of 1936, repairs were made so swiftly after dark that by midnight the ion density showed relatively only a small increase over that of 1934 midnight. Perhaps from these comparisons we may gather a broad hint of why radio reception is generally more steady at night than during the sunlit hours. For surely it is the Sun that electrifies the atmosphere into an ionosphere; if so, it is reasonable that changes in position of the Sun in the sky, changes in the distance of the Sun from the

Earth, and changes of the surface features on the face of the Sun may affect the degree of our electrification.

There are, of course, bombardments other than the solar radiation, and these cannot be ignored. Recently A. M. Skellett of the Bell Laboratories made a list of all the radiant sources of atmospheric ionization known to us, computed their probable energies, and arrived at this line-up:

Ultra-violet light from the Sun..............	28.35
Meteors during morning meteor shower.......	2.4 (maximum)
Ultra-violet light from the stars..............	0.014
Cosmic rays...............................	0.00031
Meteors, average for normal day, A.M.........	0.00024
Meteors, average for normal day, P.M.........	0.00012
Ultra-violet light from full Moon..............	0.000044

The numerals refer to units of energy per unit of area intercepted by the Earth per second. Note that the solar ultra-violet represents more than ten times the energy of all the other sources combined. This is not because it is more energetic than the stellar ultra-violet or the cosmic rays, but because there is so much more of it. All authorities agree that the solar ultra-violet is one of the most active agencies of atmospheric ionization. E. O. Hulburt and H. B. Maris, of the Naval Research Laboratory, regard the solar ultra-violet as the dominating agency, responsible for more than 99 per cent of the ionization of all the various layers of sky lands. It is known that enormously more ultra-violet sunlight reaches the upper air than ever gets through to the Earth. It is also known that fluctuations occur in the ultra-violet radiation of the Sun, sudden outbursts at times of sunspot appearance, and these bursts and spots often are followed instantly by violent shifts in the ionosphere. The evidence for ultra-violet influence as a leading actor in the invisible drama of ionization is strong. But some authorities have doubted whether the ultra-violet was the whole show.

Several years ago S. Chapman of the University of London suggested that high-speed electrons or other par-

ticles ejected by the Sun could account for some of the ionization. More recently another corpuscular theory has been proposed by L. V. Berkner and H. W. Wells on the basis of late findings at three widely separated observatories of the Carnegie Institution's Department of Terrestrial Magnetism—the station near Washington, D. C., another at Huancayo in Peru, and the third at Watheroo, Australia. A curious discrepancy has shown up in the records of these three stations with regard to the F_2 layer, whereas their records with regard to the lower layers remain in agreement with former conceptions.

The point is this: if the ionization is caused by the light of the Sun, the results should be most prominent when the Sun is directly overhead. In the latitude of Washington and other parts of the northern hemisphere this vertical position is attained in summer, in Australia and other southern latitudes in winter. Therefore we should expect the ion density in July to be at a maximum over Washington and at a minimum over Watheroo, and in January to be at a minimum over Washington and at a maximum over Watheroo. This is exactly what happens so far as layers E and F_1 are concerned, but F_2 follows a different pattern of behavior. For, curiously, the F_2 ionization is at its highest density during the months of November, December, January, and February *both* at Washington and at Watheroo, and at its lowest during the summer months at *both* stations. Reports from the equatorial station at Huancayo show the same conditions for F_2 over Peru. Apparently F_2 is at its maximum at all latitudes at the same time, irrespective of the altitude of the Sun, while the density of the two lower layers of ionization follows the Sun's course along the ecliptic rather closely. From these and other considerations Berkner and Wells reason that the agency which smashes the molecules of the uppermost atmosphere to form the sunlit bulge we call F_2 is not the same as the agency which penetrates deeper to form F_1

and E layers. And yet both agencies must come from the Sun, since there are certain daily and seasonal and sporadic effects in all layers which seem to keep step with certain solar changes. It is the hypothesis of Berkner and Wells that ultra-violet light is responsible for E and F_1 ionization in the normal phases of these lower layers, and that particles of matter shot out of the Sun are responsible for the F_2 ionization. It is known that vagrant calcium is abundant in the solar atmosphere, and atoms or molecules of such an element ejected from the Sun at high speeds might mutilate and agitate the particles of our upper atmosphere in the peculiar rhythms of the F_2 layer. Another item cited in favor of this corpuscular theory is the behavior of the ionosphere during the solar eclipse of June, 1936. As soon as the Moon covered the face of the Sun, there was a pronounced drop in the ion density of both E and F_1 layers, suggesting that their source of ionization had been shut off. But the ion density of F_2 showed very little change. Ultra-violet light travels at the speed of 186,000 miles a second, and any interruption of its beams at the Moon's distance should be felt in less than 2 seconds; whereas corpuscles, such as molecules or atoms, travel only a few miles a second, and those already past the Moon would require many minutes of travel to reach the Earth.

The corpuscular hypothesis is proposed by its authors as a tentative explanation, subject to the testing of more extensive observations. Recently they perfected an automatic radio sounding device which is expected to provide the more complete record that is wanted. This apparatus is driven by a motor and operates continuously, twenty-four hours a day. It transmits a series of signals of changing wave length, beginning at 18.8 meters and gradually shifting to longer and longer lengths until 583 meters is reached, whereupon it reverses and repeats the sequence. Fifteen minutes are required to each series; therefore the machine runs the gamut of its wave lengths four times

every hour. At the same time, a photographic device records the reflections and other behavior of the waves. One of these machines is now operating in the station near Washington, another at Huancayo, a third at Watheroo; and others may be installed at strategic points on other continents. The idea is to obtain a continuous record of what is happening in the upper air—and this robot has shown up in all tests as a peculiarly apt, dependable, and never-sleeping observer.

4

The lowest ledge within the ionosphere averages about 70 miles above ground, and the highest occasionally reaches 300 miles. The material of this upper region cannot be called air in the strict sense, for only the lightest atoms could rise to such altitude, and perhaps only the lightest fragments of these exist there; consequently the texture of this outer atmospheric stuff is the thinnest imaginable. And yet, rare as it is, the gas is hot. It bulges ever toward the Sun, the author of its heat. Here, in this thin, hot, continually changing bulge of electrification, is the radio's last barrier. Any wave that can pierce it would be lost—or so we think.

But one night in 1927, J. Hals, a radio engineer of Norway, was listening in Bygdö to code signals vibrated by a short-wave sending station at Eindhoven, Holland. The signals were coming through sharp and clear, when presently Hals became aware of a delayed echo. He timed the echo and found a lag of 3 seconds. This was amazing! Radio travels 186,000 miles a second; therefore a 3-second delay in the reception of the echo suggested that the wave had traversed three times that distance—or about 279,000 miles out and an equal span back. This is beyond the Moon's orbit, and it seemed incredible that any wave which had escaped that far could be reflected back to the small target which is the Earth.

Hals's announcement caused a stir, and preparations were made for special tests. Signals of enormous strength were propagated, so strong indeed as to be painful to the ear; and to several listeners in northern Europe the echoes came back firm and distinct—some 3 seconds later, some 5, a few 15. A French eclipse party in Indo-China in 1929 reported hearing delayed echoes of 30 seconds—time enough for a radio impulse to travel more than 5 million miles.

Who can explain this mysterious effect?

Appleton, of London, and van der Pol, of Holland, have suggested that the delay may be caused by a trapping of the radio waves in the ionosphere. Possibly the impulses are caught between the changing layers of ions and oscillate back and forth in their prison for a while, until some fluctuation opens a way of escape and they bounce back to the ground.

More attractive to the imagination is the hypothesis proposed by Carl Störmer, the distinguished Norse geophysicist. Professor Störmer believes that the aurorae, those flickering arcs and curtains of light which are familiar sights in the polar skies, are caused by streams of solar electrons impinging on the magnetic field of the Earth. The fact that the Earth is a rotating magnet necessitates that there be such a field, or peculiar configuration of space, extending out from it and surrounding it; and the fact that compass needles respond and point as they do is direct evidence of the existence of the field.

Now, this magnetic field extends far beyond the atmosphere, possibly for hundreds of thousands of miles. It operates to shield off from the equatorial and temperate zones of the Earth the continual rain of electrons shot out from the Sun, and causes these particles to flow in long curving paths toward the two magnetic poles—so Störmer infers. Such a flow would constitute a continually moving but fairly uniform electronic structure in the form of a vast hollow ring surrounding our planet, a sort of vacuous

doughnut with the Earth at its center. The inner, opposite surface of this hollow ring, according to Störmer, is the distant mirror that reflects the echoes which Hals and others have heard.

Neither of the explanations is free from serious criticism, and science is still groping for light on this peculiar phenomenon. A curious detail is the fact that the echoes have never been heard in North America, though on several occasions special signals have been sent on very powerful transmissions, and delicate detectors have waited attuned to pick up the echo.

5

An investigator in the United States has discovered what may prove to be an even more significant gesture from Out There. He is Karl G. Jansky, an engineer of the Bell Telephone Laboratories. His work is centered at the short-wave experiment station near Holmdel, New Jersey, where three farms were bought and consolidated into a tract of four hundred acres. Here radio researchers find elbow room and sanctuary from interruption, and in this quiet retreat, isolated from surface noises, they try to unscramble etherial noises—static, for example.

The familiar static that occasionally rasps its atmospheric jazz into a Metropolitan Opera broadcast—or, with equal indifference, into the antics of a tooth-paste comedian—has been the subject of much study by a group of able analysts of long-wave radio phenomena. But scarcely any attention had been given to static affecting short-wave reception until the present decade, when Jansky took up the problem. In particular, the authorities needed to know if the static came from a definite direction. To get at that question Jansky rigged up an antenna on a rotating platform.

G. K. Chesterton used to sponsor a precious notion to the effect that useful devices of civilization originate as toys or

playthings. Jansky's rotating antenna would fit neatly into Chesterton's theorem, for here is a merry-go-round turned to scientific research. The thing is 90 feet long; it rides on wheels fitted to a circular track and is driven by a motor which moves the frame so leisurely that 20 minutes are required to make a revolution. All night and all day it rotates, as constant as the Earth on the polar axis. And as it thus inclines an ear to each point of the compass in turn, a sensitive apparatus traces a continuous record of whatever is heard.

Soon after this scientific eavesdropping began, Jansky recognized among his records three distinct kinds of static. First, there were intermittent noises of the crash type which were traced to local thunderstorms. Then, classed as a second type, he heard a weaker but more steady crash-and-rumble, attributable to discharges of distant thunderstorms whose radiations are reflected from the Kennelly-Heaviside layers. Finally, the third type, a steady hiss. The source of this hiss was not obvious, and eventually all Jansky's attention was concentrated on it.

The crashes and rumbles of the first and second types of static might come from any direction, but the hiss betrayed a definite point of origin, though the point progressively changed during each day, and from day to day. It was as though someone out in space were broadcasting messages and at the same time were revolving round the Earth. "It never quite completed the circuit, though," observed Jansky, "but when it reached the northwest the hiss would die, and at the same time a similar hiss from the northeast began to make itself heard. This new source of static would then gradually shift in direction throughout the day until the northwest position was attained, when it died—and so the process repeated itself, day after day."

At first Jansky thought the Sun marked the direction of origin of this mysterious signal, but as the year advanced and the Sun changed its position among the stars, the static

did not follow it. Then the whisper seemed to proceed from the point in the sky opposite the Sun, but again continued observations showed that this was not so. Finally, evidence pointed to the position of the Milky Way system of stars as the direction; and subsequent observations and mathematical analysis of the whole body of data confirm this.

The effect is weak. Only a sensitive apparatus can detect it, but to this acute radio ear it is unmistakable. As soon as the rotating antenna turns toward the Milky Way the disturbance begins; it grows in strength until the region of the constellation Sagittarius is reached; after that it weakens and gradually ceases as the opposite side of the galaxy is reached. Since the Sagittarius region marks the center of the Milky Way, and is believed to be the most densely packed zone of our stellar system, it seems reasonable to attribute the effect to the stars. Accordingly the hiss has been named, "cosmic static."

Cosmic static is not to be confused with cosmic rays. The latter are detected as an ionizing agency in vacuum tubes and electroscopes, whereas cosmic static has made itself known only as a wave attuned to a radio receptor of 14.6 meters. That happens to be the wave length of the antenna used by Jansky in his discovery. A further investigation is planned, to use antennae of various wave lengths. By these means it should be possible to go up and down the scale to find the limiting wave lengths within which the cosmic static operates. While it manifests itself in the detector as a wave, it may possibly be a secondary effect caused by missiles of a corpuscular nature striking the atoms of the upper atmosphere. Here is a rich and inviting field for further research.

6

There is still another apparition, a luminosity of the night sky that may be seen by the unaided eye. It is difficult to detect when the Moon is up, or where there are street

lights or the glare of a neighboring city; but under favorable conditions, and especially in the spring, the effect becomes visible shortly after sunset—a faint band of haze arching up from the western horizon. In the autumn it assumes the same form in the eastern sky before sunrise. For centuries this has been called the zodiacal light. On a very clear night, particularly in the tropics, the zodiacal light may be traced entirely across the sky as a luminous belt. And at midnight the part of this belt which is overhead glows more brightly. This more luminous patch is called the counterglow, or *gegenschein*. But naming a thing does not solve its enigma, and the zodiacal light and its counterglow have long been an astronomical puzzle. Numerous theories have been advanced. They range all the way from Cassini's idea of a cloud of meteoric particles surrounding the Sun to E. E. Barnard's less spectacular idea of refracted sunlight.

But more recent, and particularly fascinating because of the graphic picture of our planet which it presents, is the hypothesis proposed by E. O. Hulburt as a result of his study of the ionosphere. Hulburt, as I have mentioned earlier, explains the ionosphere in all its layers as produced by the bombardment of ultra-violet rays from the Sun. He sees the zodiacal light as of a piece with these other phenomena of the upper atmosphere. It too is an effect of air particles electrified by the solar ultra-violet.

Originally, of course, our air particles are neutral, *i.e.*, unsmashed molecules. But like the molecules of all gases they are perpetually on the go, and as the atmosphere heats under the Sun's rays the particles move faster, with a general tendency to move upward. Many of them acquire speeds that carry them through the sunlit F_2 region and far beyond, to distances 20,000 to 50,000 miles from the Earth. But by the time they have attained these distances the solar ultra-violet has got in its work; practically every air molecule is now ionized. Once ionized they are charged fragments, and as such are trapped by the Earth's

magnetic field, their outward flight being checked by the attractive forces of our rotating terrestrial magnet. Thereafter the ionized fragments go wherever the force of gravitation and the pressure of light take them. The combined effect of these two forces is to cause the particles to drift horizontally eastward and westward around the Earth and finally, under the pressure of sunlight, to trail off in the direction away from the Sun. Thus on the day side of the Earth the particles never rise higher than about 50,000 miles, but on the night side they trail off into space, and the sunlight whose pressure distends them also stimulates them to fluoresce. Hence they are visible, and this stream of visibility may extend into the Earth's night shadow for as far as a million miles, according to Hulburt's computation.

Such then is the zodiacal light. This distended cloud of electrified fluorescing particles is what we see after sunset, and before sunrise, as the arching band of haze pointing upward and away from the sunken Sun.

At midnight the distended cloud is directly above us, and it is then that there appears at the zenith the brighter area of the counterglow. The counterglow, says Hulburt, is only the center of the cone of the zodiacal light seen from below.

What a picture! Our "round and delicious globe" attended by this thin cometlike tail—a million-mile plume of electrified particles that we trail through space as we ride our annual circuit round the Sun at 19 miles a second, and travel with the Sun toward Vega at 12 miles a second, and partake of the rotational motion of the Milky Way in still another direction at an estimated 175 to 185 miles a second. One might think that, with all these motions to accommodate itself to, our plume of electricity might get bent or tangled. But not so, says the theory: the persistent pressure of light both creates and molds it; so the plume always points away from the Sun, always trails the night side of the Earth.

Thus, according to physicist Hulburt, the zodiacal light is the last vestige of the Earth's atmosphere. This outermost stuff of our planet is too thin and subtile to reflect radio waves. Perhaps it may be thought of as dust from the radio roof—cosmic dust blown into space by the wind of light that forever is rushing through the world. Perhaps some of this far-driven Earth stuff is captured by a passing planet or meteor. Or it may escape, to travel its own course for millions of years—solitary, relic of Earth, stuff for the future, symbol of man adrift, tugged at by all the Universe, beaten upon by all the radiant forces, but persisting somehow in that unity of nature which makes the whole creation kin—man and stars.

Chapter III · THE SHINING STARS

The Daughter: Still, the stars are shining.
The Uncle: Ah! stars—that's nothing.

—M. MAETERLINCK, THE INTRUDER

THE nature and behavior of the shining stars are betrayed by their invisible atoms, and lately these have been telling some astounding facts of the stellar energy we live by and the stellar universe we live in. Perhaps no quarter century since Galileo's time has opened such astronomical vistas for the mind to explore as has ours. New instruments of research, new methods of decoding the messages that continually bombard us, fresh attitudes of mind, and unconventional approaches to ancient enigmas have given astronomy a golden age. Perhaps it is only a prelude to what we shall have in the 1940's when the 200-inch telescope is safely poised on its mountaintop and the Otherness beyond our present seeing becomes dominions of man: this curious, prying, stumbling, aspiring, persistently hopeful creature, half brute who clings to his practical clod, half god who looks through distant light-years where the stars are shining.

They shine by a mystery of motion which seems to underlie all things. It is exciting to realize that in a fiery tempest of particles deep in the Sun the weather in our streets is

forged, the green magic of chlorophyll is activated, and the delicate rhythms of protoplasm, of consciousness, of mind, are shaped. From the shining stars we learn of processes of degeneration which issue at last in the massive, collapsed, opaque, nonluminous lumps known as black dwarf stars, the dark destiny that may mark the end of shining. Thus, from present stellar news we read the past and are enabled to peer somewhat into the future.

The news comes by one motion—the motion of light rays traveling at the constant rate of 186,000 miles a second—but the messages these vibrant signals bring are of three kinds of movement: the motions of atoms within stars, of stars within galaxies, and of galaxies within the Universe.

I

The motions of stellar atoms are detected by means of the spectroscope. The heart of this device is a transparent prism which breaks up light into its rainbow pattern of colors; but in practice the prism requires a complicated mounting of accessory apparatus, including a telescope mirror or lens to collect and focus the light and a photographic plate or film to record the image. Some years ago George Ellery Hale added still further auxiliary equipment to the prism device, and, by an ingenious mechanical arrangement, provided an apparatus which would show the image of the Sun as seen in the light of a single one of its incandescent elements. With Dr. Hale's spectroheliograph it was possible to make a photograph of the Sun in the violet light of its glowing calcium, or in the red light of its glowing hydrogen, or in the other tints that glow with sufficient intensity in the solar crucible. Such photographs, by shutting out other rays and giving a hydrogen view of the Sun, or a calcium view, reveal details which are lost in the tumult of mixed elements, each vibrating its distinctive spectral colors. By means of Hale's device, moreover, it was possible to eclipse the Sun artificially, and thereby to

bring into sight at will the great tongues of flame known as "prominences" which continually lick out from the Sun's edge. The existence of these solar flames was known long before this time, and by opening the slit of the spectroscope wide it was possible to observe an individual prominence. But Hale's spectroheliograph added an important advantage: with it the astronomer could photograph on a single plate *all* the prominences flaring out from the solar disk at a given moment, and thus obtain a complete record of the Sun's encircling flames.

In the summer of 1936 still another advance in our apprehension of star stuff was made by Robert R. McMath and his associates of the University of Michigan. They adapted Hale's apparatus to a motion-picture technique, building for the purpose a huge movie camera in the form of a 50-foot tower at Lake Angelus, Michigan. By a reflection of sunlight from the clock-driven mirror at the top of the tower, down to the lens at its bottom, and thence through the spectroheliograph to the moving ribbon of film, McMath and Edison Pettit (the latter from Mount Wilson) obtained a series of pictures of the Sun in action—action of a sort that astonished the professionals of the American Astronomical Society when the first public showing of the solar movies was given at the society's dinner in Cambridge in the autumn of 1936.

Here was a continuous record of the swift vicissitudes of calcium gas in the Sun's hot atmosphere. Flaming streamers were seen to form and lick upward, some of them for tens of thousands of miles, others flaring horizontally along the curving edge of our star like a vast prairie fire fanned by a hurricane. There were successive fiery jets of matter apparently shot out of sunspots or other disturbed areas, dart after dazzling dart like the successive discharges of a roman candle, spurting upward in long parabolas at 60 miles a second and faster. Most surprising of all were the prominences that formed as luminous clouds in the high

atmosphere of the Sun, to descend in falling streamers, sweeping downward for thousands of miles toward the surface. Other pictures showed prominences of hydrogen gas, equally varied and spectacular.

"We knew from earlier studies that prominences must change their form," said Heber D. Curtis, introducing the pictures to his fellow astronomers at the Cambridge meeting, "but this is the first unbroken record of the processes of development as they occur in the different types of prominences. It seems out of the question now to regard the pressure of light as the sole cause, or even as the most important factor in such displays. The apparent start of the clouds or streamers in the high atmosphere of the Sun seems to argue some important contribution of electrical action."

Perhaps our star, like our planet, has its peculiar roof of electrification. We know that the corona, the pearly crown which is visible only at times of solar eclipse as a surrounding halo, changes its form as the sunspot cycle waxes and wanes. Sometimes it is an oblong arrowlike shape, as though the forces which distend it were greatest along one line of direction; at other times it is more nearly circular, but always the outer edges are ragged and irregular. Characteristically the brightness of the corona about equals that of the full Moon. But at the 1936 eclipse, as photographed in Asia by the expedition from Harvard College Observatory and Massachusetts Institute of Technology, the corona shone with the brilliance of more than fifty full Moons. Logically we should expect a variable star to have a variable envelope.

Just how this envelope forms, and of what substance, is unknown; but it is probably safe to say that in the corona we see sun stuff at its thinnest, that here we have the outer mists of the solar atmosphere. Suppose, in our asbestos-clad imagination, we penetrate the corona and push through it to the central Sun. We encounter denser and yet

denser concentrations of gas, and higher temperatures, until we reach a level at which the solar material becomes opaque. Ripples continually mottle this stratum, appearing as a granulated structure whose perpetually undulating "rice grains" measure more than 2000 miles across. The temperature here is about 10,000°F., generally known as the surface temperature of the Sun. This turbulent "surface" is still gaseous, however, and beneath it the density increases and the temperature rises until we reach the center of our star. The central temperature measures about 15,000,000°—and it appears that practically all stars, irrespective of their considerable differences in size, have approximately this same central temperature, although surface temperature varies from star to star over a wide range. At the solar center the material is compressed to a mass denser than solid metal. And yet, amazingly, this central stuff is not solid, not even liquid—it is a gas throughout!

There was a time, not many years ago, when it was believed that the Sun is a liquid star. This idea arose from the fact that if you take the mass of the Sun and proportion it to the volume, you arrive at an average density about one and a half times that of water. Other stars similarly proportioned show an average density greater than that of solid iron: the red dwarf known as Krueger 60 is an example. Still others are yet more dense—the white dwarf Companion of Sirius has stuff so concentrated that it averages about a ton to the cubic inch. At the opposite extreme of stardom are the red giants—such as Antares and Betelgeuse—enormous balloon like bodies with an average density less than that of the Earth's atmosphere. Sir Arthur Eddington found a certain relationship for the gaseous stars—a ratio such that if you know the mass of a star you can determine its absolute brightness (or, if you know its brightness you can determine its mass), and then from these two values you may derive its other conditions and

so describe the internal mechanism. One day, just to see what would happen, Professor Eddington tried his formula for gaseous stars on the Sun. He was surprised to find that it worked. Then he tried it on the denser Krueger 60, and again the mass-luminosity relation as prescribed by the law agreed very closely with the observational evidence. But this mass-luminosity relation could work only for gaseous material; it had no applicability for liquids and solids. There was just one reasonable conclusion: the Sun, though denser than water, and Krueger 60, though denser than iron, must be accepted as gaseous stars.

But how can a substance be so closely packed, so concentrated, and yet remain a mobile gas? The secret, answer the physicists, lies in the process of ionization—that process of atomic mutilation with which we are already familiar from our studies of the Kennelly-Heaviside layers of our atmosphere. Atom smashing facilitates atom packing. The atom of iron, for example, a metal that exists in abundance in the Sun, consists of a central nucleus surrounded by twenty-six revolving electrons. The electrons move in orbits at various distances from the nucleus. The distances are such that if an atom of iron could be magnified until its central nucleus became just visible (about the size of a pin point), the outermost electron orbit would be about 6 feet from that center. If you detached the two electrons which travel this outermost path, your iron atom would be considerably smaller, slightly mutilated, but still iron. If you then removed the fourteen electrons which ride the next outer orbits, you would drastically reduce the diameter of the atom; but since the nucleus would remain intact, and since the nucleus is the predominant determiner of atomic character, this reduced structure would still be recognizable as iron. Under extreme conditions it might be possible to strip off the eight electrons of the next shell of orbits, and leave a residue consisting only of the iron nucleus and the two innermost encircling electrons—a structure so small

that millions of such fragments could be contained in the space that originally was occupied by the whole atom.

In addition to iron there are platinum, copper, sodium, oxygen, helium, and fifty-five other chemical elements in the Sun. All are subject to the pressures generated by the gravitational effect of this huge aggregate of particles, each atomic mass attracting its neighbor masses, and also subject to the random movement which is characteristic of gas particles. The greater the gravitational pressure, the heavier is the crushing effect, the more violent is the agitation, and in general the higher is the temperature. It is these processes that cause atoms to bump head on, to knock particles out of one another, to strip off whole shells of electrons in the case of some, and to turn the interior of the Sun into a turbulent mob of almost naked nuclei and free electrons. Because they are so stripped they require less than normal space, and, despite the excessive concentration, the particles enjoy a freedom of movement sufficient to class them as a gas. I have mentioned the Companion of Sirius, in which the gas is so dense that it weighs a ton to the cubic inch. Recently G. P. Kuiper studied another white dwarf star of even more extraordinary properties. Its diameter is only half the Earth's, but its mass is nearly three times the Sun's—which means that its material averages about 620 tons to the cubic inch. A penny minted of such material would weigh more than a motor truck.

No eye can pierce the opaque undulations of the solar body. But, knowing that the material is gaseous throughout, and knowing by laboratory experiment what happens to gases with increase in pressure and temperature, astrophysicists are able to picture the tumultuous interior of the Sun. They find that at 15,000,000° the gas will generate all its radiation in the form of x-rays. And they can calculate the congestion and the collisions that such temperature produces.

"Crowded together within a cubic centimeter there are more than a quadrillion atoms, about twice as many free

electrons, and 20,600 trillion x-rays," reports Eddington, and his units are of the British order which reckons a trillion as a million million million. "The x-rays are traveling with the speed of light, and the electrons at 10,000 miles a second. Most of the atoms are hydrogen, or rather, since they have lost their satellite electrons, simply protons [*i.e.*, hydrogen nuclei] traveling at 300 miles a second. Here and there will be heavier atoms, such as iron, lumbering along at 40 miles a second. I have told you the speeds and the state of congestion of the road; and I will leave you to imagine the collisions."

The Sun thus may be likened to a huge x-ray tube. The beneficent heat and light which flood from it through space are simply the softened residue of such solar x-rays as manage to escape. It takes only about 8 minutes for a dart of sunlight to travel from the "surface" of the Sun to the Earth, but that same dart may have caromed about within the crowded interior for thousands and even millions of years, repeatedly robbed of energy in its innumerable collisions with atoms, until finally what started within the dense central tumult as a short wave of invisible x-radiation escapes as a long wave of blue, green, red, or some other visible color.

The source of this energy we do not know positively, but an increasing number of investigators are inclined to believe it is by atomic synthesis, rather than by atomic annihilation, that the solar x-ray tube is empowered. One-third of the Sun's mass is hydrogen, which leaves the remainder to be distributed among the sixty other known solar elements. Perhaps there was a time when the proportion of hydrogen was greater. Indeed, some theorists suggest that "in the beginning was hydrogen," and that all the more massive and more complicated atoms are the results of mergers of hydrogen atoms. A hydrogen atom weighs 1.008 units.

Four hydrogens, weighing 4.032, may combine to form one atom of helium. But by oft-repeated test it has been

found that helium weighs only 4.003, which means that .029 of the hydrogens does not enter into the helium. What becomes of it? The answer, say the physicists, is simple: this surplus hydrogen stuff is transformed in the process from mass into energy, and is radiated as an x-ray. Similarly, sixteen hydrogen atoms (or four helium atoms) may merge to make one oxygen atom, with an even larger difference in mass translated into energy. We believe it is in such ways, by repeated fabrication and rebuilding of their units of matter, that the stars continue to shine.

An important factor in these changes is the balancing of two effects: the effect of gravitation, tending to contract the star, and the effect of the outpouring radiation, operating to distend it. If the equilibrium is disturbed in one direction, the star may expand. This response may be followed by a contraction, and thus the star appears to pulsate. With a more violent or more critical disturbance of its balance, the star might even explode.

Most of the hundreds of thousands of stars that have been studied appear to be in a state of fair stability, but there are a few thousands that vary quite noticeably. Some of them change irregularly. In October of 1936, for instance, the second magnitude star Gamma in the constellation Cassiopeia increased its brightness 60 per cent within a day, and then over a period of weeks slowly faded to normal luminosity. Other variables are more regular, and the group known as Cepheids appear to be true pulsating stars, alternately brightening and dimming in fixed periods of hours, days, and weeks.

Whether the upflare of Gamma Cassiopeiae represents a thwarted explosion, or is preliminary to a future one, we do not know; but there are other recent stellar events whose explosive nature can hardly be questioned. Thus, during 1936, four faint stars within the Milky Way suddenly, overnight, became very bright. One of these novae—or new stars, as they are called—lighted up in June in the con-

stellation Lacerta, the Lizard. The next appeared in July in Aquila, the Eagle, and in September still another nova burst forth in this same constellation Aquila. Finally, in October, came the appearance of yet another new star in Sagittarius. In each case, the star increased its output of radiation by several magnitudes within a few days.

The nova in the Lizard was especially brilliant. Photographs taken a few hours apart showed the formation of four successive shells of expanding gas, one moving 2200 miles a second. The intensity of the calcium lines in the spectrum of this star enabled J. A. Pearce, at the Dominion Astrophysical Observatory in Canada, to measure its distance as about 2600 light-years. Independently C. S. Beales made the measurement at the same observatory, and Merrill and Wilson did so at Mount Wilson, and all obtained the same value. It is the past that we are studying in the light of these distant orbs: the explosion which brought an unknown star into conspicuous view of the Earth in A.D. 1936 really occurred centuries before Christ. Soon after its discovery in June this nova showed as of the second magnitude; but by the beginning of 1937 it had faded to the tenth and could be seen only with the aid of a telescope.

There is much speculation as to what happens in these gigantic outbursts, and what follows the fading of the star to mediocrity. Do the shells of expanding gas escape from the star? Or are they held by its gravitational influence, perhaps to cool and condense into smaller bodies subsidiary to the main body? Gustav Strömberg, of Mount Wilson Observatory, has suggested that planets may be condensed fragments of a nova explosion. "If this is true," says Dr. Strömberg, "a nova outburst is a signal that construction work on new abodes of organic life has been started." Perhaps a new Earth, destined after its geological evolution to produce its peculiar flowering of life, was spawned out there in the direction of the celestial Lizard 2600 years ago. It may be that our Sun too had its nova outburst, in some remote past, and by the grace of that

catastrophe gave birth to Mercury, Venus, Earth, and the other planets of the Solar System—merely a surmise, but interesting.

It is possible that an explosion such as produces a nova may split the star in two, or at least break off a sizable part of it. This seems to have happened to the nova which flared up in Hercules just before Christmas of 1934. Watching this magnificent luminary at Lick Observatory in the summer of 1935, Dr. Kuiper saw that the star had separated into two pieces, one shining about half a magnitude brighter than the other. With the 40-inch refracting telescope at Yerkes Observatory, George van Biesbroeck followed the movements of these two large fragments over a period of months. They continued to separate, and at the beginning of 1937 the distance between them was more than two hundred times the distance of the Earth from the Sun. It is possible, of course, that we are witnessing here the birth of a double star, but many astronomers are inclined to doubt this. They think that the "companion" which is about half a magnitude fainter than the other is really a smaller mass of gas at high temperature—*i.e.*, a part of the ejected material—and that the main body of the star remains intact.

A more plausible theory of the birth of double stars attributes the event to the capture of one star by another. Similarly, a nova has been explained as the result of a near approach of two stars.

The light rays which report these far-off events, remote in time as in space, tell the temperatures, the nature of the agitated gases, their tumults of atomic action and reaction. But as to causes of these catastrophes their messages are less definite. And we are left to speculate.

2

Superficially, the motions of stars through space appear to be almost as random as the motions of atoms and electrons within a star. Each of these shining bodies seems

to have its individual direction of going: some advancing, some receding, some heading eastward, others westward, still others along diagonal paths. Many are traveling alone, like the free electrons in the stellar interior. Others are moving in couples as double stars, or in families as clusters of many stars. The velocities range all the way from the Sun's 12 miles a second, and even slower for a few sloths, to 700 miles a second for a swift giant in Cepheus, the King. In spite of these diverse directions and velocities, the stars do not barge off into outer space. They appear to be held by some primal law into a unified system, the swarm which the Greeks named the Milky Way. One of the great detections of our time is the discovery that the vast swarm itself turns in a whirlpool motion of rotation.

Rotation, it would seem, is a universal principle of physical nature. The electrons within atoms spin on their axes as they revolve round their central nuclei, and there is evidence that the nuclei also rotate. The Earth, as it travels its orbit round the Sun, imitates the rotating electrons, and so do the other planets. We know by observational tests that the Sun rotates. By virtue of the Sun's rotation and the revolutions of the planets, each at its individual velocity, the Solar System continually turns as it plows its course through space in the gravitational grip that directs it. And now we detect, amid the medley of apparently random stellar motions, this overruling systematic motion of rotation round a dynamical center.

We have found, first by Harlow Shapley's researches, later confirmed by others, that this center lies in the direction of the great star cloud in Sagittarius.

We have measured the velocity of the rotation, guided by the theory of B. Lindblad of Sweden, tested by the observations of J. H. Oort of Holland, then confirmed and extended by the more numerous observations of J. S. Plaskett and J. A. Pearce of Canada. Just as the planets move round the Sun at velocities which vary with the dis-

tance, the nearer the planet the faster its speed, so do the stars move round the dynamical center of the Galaxy. At the Sun's distance from the center, the rate appears to be about 175 miles a second—some authorities say 185. And the period of rotation of the system is 225 million years—it takes that long for the Milky Way to make one turn.

Most of these findings rest on actual measurements of individual stellar motions. The rotational effect is not discernable in the light of near-by stars but becomes more apparent as the distances increase. Because of this our surveyors have confined their search to beacons not nearer than 1000 light-years. Oort had measurements for about 300 such stars; Plaskett and Pearce clocked the speeds of about 850 others. Thus, close to 1200 star records were available. Their testimony was remarkably unanimous. Each showed a motion which spoke of the Milky Way rotation.

But our Galaxy contains millions of stars. According to the estimate of Frederick H. Seares, made at Mount Wilson Observatory on the basis of counts of stars in representative regions of the skies, the Milky Way aggregate must be not less than 30,000 million stars and may be 40,000 million. But whatever the luminous population of the Milky Way may be, it is certainly many thousands of millions—and what are 1200 measured stars among that multitude? Astronomers wish to extend their evidence. They want thousands instead of hundreds of witnesses. And they are eager for news of yet more distant members of this celestial swarm. Recently, at the Harvard College Observatory, Bart J. Bok and S. W. McCuskey put to use an improved technique of measurement which should add a thousand stars a year to our list, and swiftly accumulate the fuller data which the galactic surveyors desire.

Bok and McCuskey's method is not so much new as it is a refinement of a proposed extension of an old method. In the old method, a telescope is focused on a star, and the light from the star is then passed through a prism and

spread into its spectrum. Meanwhile, light from some source in the laboratory is also passed through the prism, and both the spectrum from the star and the spectrum from the laboratory are photographed on the same plate. If the lines of the stellar rainbow do not coincide in position with lines of the corresponding element in the laboratory rainbow, the astronomer concludes that the star is in motion—approaching, if the displacement is toward the violet end of the spectrum; receding, if toward the red. For distant stars the work is tedious. Hours and sometimes days are spent getting a legible record from a single star.

Some years ago E. C. Pickering, G. E. Hale, and F. L. O. Wadsworth suggested a variation in this strategy. Instead of directing the light from the telescope into the prism, place the prism in *front* of the telescope lens and take a photograph of the result at the focus of the telescope. In this way, the light of all the stars within view of the telescope is first passed through the prism, and each stellar image is separated into its spectral lines before it reaches the lens. The resulting photograph shows not one spectrum, but many—one for each star in the field—and in this way as many as 200 stars have been spectrographed at the same time on a single photographic plate.

But the problem is not only to get the spectral images of stars, but also to add a laboratory spectrum to each stellar spectrum so that the shift of the lines may become apparent. R. W. Wood pointed out that there are certain chemicals—neodymium compounds, for example—which might be used to provide the comparison. And it is this chemical device that the two Harvard astronomers, Bok and McCuskey, put to such successful use in 1936.

They placed their prism in front of the telescope lens, as described. And behind the lens, in front of the photographic plate, they placed a thin glass cell containing a solution of neodymium chloride. This liquid, although it is transparent to most rays, has the faculty of absorbing certain wave

lengths of starlight, and the effect is to add a few dark lines or bands to the star spectrum. These additions, because of their stationary origin, show no shift. By this means there is photographed with each stellar image the comparison which tells whether the star is approaching or receding. Already Bok and McCuskey have accumulated important new records, and the program they have mapped out and are now pursuing promises much valuable news of how the stars move in our celestial whirlpool.

3

While astronomers are using these and other ways to extend their data to more numerous and yet more distant beacons, the physicists have applied another method of testing the rotation. This newly discovered physical evidence is the varying intensity of cosmic rays. There has been considerable controversy among the experts as to the nature of cosmic rays; but whatever the outcome of that debate may finally be, there is hardly any difference of opinion as to the general place of origin of the mysterious radiation. All evidence points to a source *outside* the Milky Way.

If the source is outside, and if our Milky Way is rotating, then the bombardment should be more intense from the direction toward which we are turning—just as a man running in a rain will get more raindrops in his face than on his back. So reasoned Arthur H. Compton and I. A. Getting, and they proceeded to look for evidence.

Our position in the Milky Way is such that as the Sun sweeps along its course round the distant center, it seems to move in the direction of the constellation Cygnus, the Swan—though, to be sure, Cygnus too is moving in the same whirl. But Cygnus is in the northern skies; therefore the direction of our rotational movement must be northerly. This should mean that more cosmic rays beat upon the northern hemisphere of the Earth than upon the southern,

and observations recently published report that such is the case.

But the Earth, as it is swung along the vast curving race-track of stars in tow of the Sun, is also turning on its axis, continually exposing a different area to Cygnus. When we see Cygnus overhead we are looking toward the direction of our galactic rotation, and at that moment the cosmic radiation should beat into our faces with an intensity greater than at any other time. Recent tests with supersensitive detectors indicate that this is the case. There is a daily variation in the bombardment of cosmic rays, and its intensity at any station in the northern hemisphere is greatest when Cygnus is overhead, least when Cygnus is on the opposite side of the Earth. South of the equator the northern constellation is never directly overhead; but at Capetown in South Africa it rises slightly above the horizon, and measurements made there show that at this moment when Cygnus is in view the cosmic-ray intensity for that region is at its height. Not only has this difference been measured, but it provides an additional index to the velocity of the Milky Way rotation. This figures about 185 miles a second, from the cosmic-ray measurements—a value which is in fair agreement with the astronomers' findings from the direct evidence of the stars themselves.

An additional argument for rotation is the fact that there are outside systems, other swarms like our Milky Way, and the spectroscope shows that the nearest of them are in rotation. The light from the more distant ones is too faint to give the effect, but the spiral and elliptical shapes of these outside systems are such as to suggest rotation, and many leading authorities are inclined to believe that whirl is a normal and universal attribute of galaxies.

Planets rotate, stars rotate, galaxies rotate. Does the Universe also rotate? Possibly. It may be that the whole sphere of space-time, with its millions of included galaxies and the invisible stuff between the galaxies, is itself the

supreme whirlpool. But of such motion, if it exists, we have no evidence, and the suggestion remains a conjecture.

There is, however, an apparent motion of the galaxies through the Universe, and certain observations have been thought to point to a remarkable uniformity in the direction of this motion. Let us turn to the evidence.

Chapter IV · SKIES ARE REDDENING

Their red, it never dies.
—HENRY AUSTIN DOBSON

PERHAPS the most publicized theory of the world as a whole is that suggested by the picture of the expanding Universe—a phrase and an idea which have been broadcast by public lectures, radio, newspapers, magazines, and books to every nook and cranny of literate civilization.

Who has not heard of the famous red shift—the curiously unanimous trend of the light of the distant galaxies when it is passed through a prism? The picture which the red shift suggested was of the Universe in process of dispersal: innumerable galaxies all rushing away, or being carried away by the distension of the cosmic bubble. It was as though the Universe were exploding, scattering itself outward at a rate which increased with distance, doomed to an ultimate acceleration at which its parts would be traveling with the speed of light, each part thereafter invisible to all the others. The most generally accepted theory of the expanding Universe predicted this sort of end—and still predicts it.

But late in 1936 and early in 1937, astronomers of Mount Wilson Observatory began to publish details of an analysis of the evidence which casts doubt on the reality of the

expansion, and makes it necessary to reconsider the whole problem of the meaning of the red shift. This startling announcement from the mountaintop in California has come like a bombshell into the camp of the theorists and is providing a major topic of conversation among astronomers, cosmologists, mathematicians, physicists, and other universe explorers. Though it concerns the vastest subject of which the mind can conceive, the nature and behavior of the Whole, and though it makes use of the powerful and highly specialized technique of mathematics to reach its conclusions, this new critical attack is quite picturable. The present chapter will attempt to outline in familiar terms what the red shift has been thought to mean, and why the accepted interpretation is now called into question.

I

That there is a red shift no one denies, for the evidence is photographic, measured, and consistent throughout. Except for a few galaxies in our immediate neighborhood, which may constitute a local group or association of Milky Ways with motions of their own, all the hundreds of others from which it has been possible to obtain a spectrum show a displacement of their lines toward the red. In studies of individual stars, this shifting of spectral lines has been accepted as evidence of motion of the stars. Thus, one reason why we believe the Sun rotates is the fact that the light from its western limb shifts toward the red, indicating that the western edge of the Sun is turning away from the observer, while the light from the eastern edge shows a displacement toward the violet, indicating a motion of approach. The other stars are too remote to show their images as a rotating disk in even the largest telescope, but from the displacements of their spectral light it has been possible to detect the general motions of approach and recession for thousands of stars. This interpretation of the

effect is the basis of the method of Bok and McCuskey in their current survey of the motions of distant stars of our home system.

The reason why these shifts of light are accepted as evidence of motion is simple. Just as a receding locomotive tends to pull the vibrations of sound from its whistle into longer waves, causing the departing whistle to howl with a deeper bass note than the whistle gives when the locomotive is standing still, so does a receding star tend to pull its vibrations of light into longer waves. But a prism is less able to bend long waves than short ones. Therefore, when the light from a receding star is passed through a prism, its characteristic lines of color and shadow are not bent so obliquely as they would be if the star were stationary. In practice, the astronomer selects certain spectral lines as landmarks and centers his attention on them. There are two bold lines generated by glowing calcium gas, known as the *H* and *K* lines of calcium, which appear in the light of practically all stars. Characteristically these lines fall in certain places in the violet region of the spectrum, and when the calcium light is generated in the laboratory or from some other stationary source the *H* and *K* lines are always found in these standard positions. But when a star which contains calcium is moving away, outward bound, the waves of its calcium rays are lengthened, the prism is less able to bend them, and they fall upon the photographic plate to the redward side of their accustomed positions on the scale. The faster the star is receding, the more drastic is the lengthening of its wave lengths, and the more redward is the position of the photographed lines. By measuring the amount of the shift, the astronomer is able to gauge the velocity of recession of departing stars, such as Aldebaran, Betelgeuse, and Capella. Similarly, by measuring the extent of a violetward shift, the astronomer may determine the velocity of approach of oncoming stars like Antares, Sirius, and Vega.

In the catalogue of stars there are about as many violet shifts as there are red shifts. Indeed, as I have said, the individual stellar motions appear to be in every direction. But in the roll call of the galaxies the vote is not divided; it is practically unanimous. Except for a few members of the local group, all of which lie within a million light-years of the Earth, the reds have it. From the outer systems, every single spectrum shows a shift toward the red.

It is this unanimity of the effect that caused many astronomers to question the interpretation. Might it not be that space has an influence on light, that light degenerates with age just as other things do, that reddening is a consequence of something that happens to the rays in their millions of years of flight through millions of millions of miles of the void?

Physicists, and particularly those physicists who concern themselves with stars, have been reluctant to admit this latter hypothesis. For if a flight of 100 million years affects a ray of light in a certain way, is it not reasonable to think that a flight of a million years would affect it perhaps a hundredth as much, and a flight of 1000 years or 10 years or 10 minutes would similarly affect it proportionately? Such questions are disquieting, for our physical world picture is based on the idea of the inviolability of light. The ruggedness of rays, their ability to endure time and perform motion without degeneration, is a cardinal principle of physics. It is recognized, of course, that an encounter between a light ray and an atom or other particle of matter may have violent consequences. Invariably, in such collisions, the light is robbed of some of its energy, and in extreme cases its quantum may be absorbed entirely by the particle of matter. But assuming no collisions, assuming that in traversing the void between the galaxies and between the stars the light escapes these encounters, science has held that a quantum could travel any distance without internal deterioration. The theory of relativity is

built on the idea of the constancy of the velocity of light. And now to question the constancy of the energy of light, to suggest that light may tire or grow decrepit with age, seems to threaten the foundations. It seems to open the way to a flock of doubts and uncertainties.

But science supremely is the art of entertaining doubts of beliefs experimentally accepted. No truth is sacrosanct. No belief is too generally approved, too well established by experiment, to escape the challenge of doubt. And no doubt is too radical to receive a hearing if it is seriously proposed.

Quite early in the discovery of the red shift of light from the distant galaxies, doubts such as these were expressed as to the meaning of the effect. The shifts were so much more pronounced than those of individual stars, indicating velocities of thousands and even tens of thousands of miles per second, that there were several critics who said at once that the red shift might mean something other than motion. But the doubters were silenced by the retort of the theorists who found that the reddening effect fitted in quite neatly with their ideas of the behavior of the Universe. For, according to the general theory of relativity, the Universe cannot stand still. Given such and such conditions, it must either expand or contract. Some of the experts held that it would first expand and then contract, a pulsating Universe. Others held that the expansion was an irrevocable tendency, that the world bubble must continually blow up with a perpetual scattering of the galaxies. There were dozens of hypotheses, each distinguished by some detail, but all grounded on the assumption that the photographic record of the red shift was evidence of the runaway motions which theory predicted.

In 1934 a practicing astronomer, Edwin Hubble of Mount Wilson Observatory, and a theoretical physicist, Richard C. Tolman of California Institute of Technology, collaborated in a new attack on the problem. Up to that time, the

only observational evidence cited in support of the expansion was the red shift. Theory called for such a shift, and the presence of the shift was accepted as a proof of the theory. But theory also called for a *uniform* distribution of the galaxies. It was only in a world where the star systems were scattered with approximate regularity that they could move in this systematic way. And so Hubble and Tolman turned from the photographs of the spectra to the photographs of the galaxies themselves, to see if the assumption of uniform distribution was supported by the actual counts. A preliminary announcement of this study was published by the two investigators in 1935, and more detailed and conclusive reports by Hubble in 1936 and 1937. The findings may be summarized quite simply.

2

Five carefully calibrated surveys of the northern skies have been made—one at Lick Observatory with its 36-inch Crossley reflecting telescope; the others at Mount Wilson Observatory, two with its 60-inch reflector, and two with the 100-inch reflector. Each telescope has its limiting distance for the kind of photographic plate used and the length of time of exposure, and the problem was to find how the brightness of the galaxies dimmed with distance. There is a law of optics which tells how it ought to dim, all other factors being equal, and thus by counting the images and classifying them according to magnitude one should be able to learn whether the spacing of galaxies thinned with increase of distance, or became more crowded, or remained uniform.

Altogether 888 satisfactory photographs were obtained, each representing a sampling of the heavens in a particular sector. Each photograph showed the images of many galaxies, ranging from the bright and comparatively near ones to the faint and remote. In this way a total of 41,069 significant galaxies were recorded. These were plotted as a

chart of diminishing magnitudes, or brightness, rated according to distance.

But the raw records, as measured directly from the photographs, do not represent the actual state of affairs. For our chart to approximate reality, certain corrections must be made; specifically, two kinds of corrections.

1. There are inevitable instrumental limitations: those of the atmosphere, those of the mirror and other optical parts of the telescope, and those of the photographic plate. Each has a distorting influence on the image as recorded. Thus, in passing through the Earth's atmosphere, the light from the distant worlds is subjected to a certain probability of collision and scattering, and in these encounters the longer waves of red light fare better than the shorter waves of blue. It follows that since proportionately more long waves get through to the telescope, the image received there is less brilliant than it would be if the telescope were poised in space above the atmosphere and so enabled to receive all wave lengths equally. Then, too, there is a selective effect in the mirrors and lenses of the telescope. Silver, which until recently was used almost universally as a coating for telescope mirrors, reflects very poorly the rays at the violet end of the spectrum. And while the new form of surfacing, aluminum, is an improvement, still even here there are certain lapses of reflection that must be measured and accounted for in this painstaking appraisal of the brightness of the remote galaxies. Not only the atmosphere and the optical parts, but also the photographic plate chooses certain wave lengths and rejects others—a selective sensitivity that no careful measurer can afford to ignore. Each of these three instrumental limitations is tested experimentally, calibrated by exact laboratory trials, and then applied to rate the images at the brightness they would show if instruments were perfect.

2. But even if instruments were perfect and transmitted all light rays without distortion, there is still a cor-

rection inherent in the light itself—a correction that must be made to care for the changed energy of the light. For, although the longer wave lengths of red are more successful in penetrating the atmosphere than are the shorter wave lengths of blue, the redder light is actually endowed with less radiant energy. Therefore, an image of an object projected with red light will appear not so bright as an image of the same object projected with blue light. But we know that the true image of a distant galaxy is bluer than that which appears in our corrected photographs—because the *H* and *K* lines generated by its violet calcium light show their redward shift, revealing that their rays arrive with less energy than they carried at their start. It is clear from this analysis that the images we receive are less brilliant than they would be if there were no red shift. Therefore, this energy effect must be reckoned for each galaxy and the magnitude of its image changed accordingly.

All these minute details were very carefully investigated and measured by Hubble and Tolman. And when they were applied as corrections, the chart of magnitudes assumed a form which declared the distribution to be uniform. Former discrepancies disappeared. The counts now indicated that the galaxies dimmed at a rate that was approximately constant, suggesting that these huge stellar swarms are scattered fairly evenly through space. Here and there clusterings are found, and in these clusters of galaxies the density exceeds the average. But on the whole Hubble reports that the Mount Wilson samplings, reaching to a distance of about 400 million light-years, show a reassuring uniformity, with the galaxies spaced on the average about 2 million light-years apart. All this agrees with our common-sense idea of a harmonious, balanced Universe. Also it is in accord with the relativists' idea of an expanding Universe.

But, hold a moment. If we are to assume an expanding Universe, there turns out, say Hubble and Tolman, still another correction that must be made. For if these distant

objects which we see in our photographs as faint spots of light are all running away from us, then their outward motion must affect the quantity of light which reaches us from them. The number of light units, or quanta, received from a receding body in a second of time must be less than the number from a stationary body. Therefore we revise our ratings to care for this third correction:

3. The number effect. This effect may be computed from the velocity of the object. One of the photographed galaxies has a red shift so considerable that its velocity of recession figures about 25,000 miles a second—assuming, as we are here, that red shift is an effect of recession. This velocity is more than an eighth the velocity of light, and it is only a problem in computation to reckon the number of quanta per second that would be subtracted from the normal number by such a speed of withdrawal. There are other galaxies with red shifts which indicate velocities of 15,000 miles a second, a speed of withdrawal which would affect the number of arriving quanta by its proportionate smaller amount. And so with galaxies of lesser shifts, indicating lesser speeds of recession: each can be calculated, the number effect arrived at quite exactly, and the correction applied.

Let us make sure that we understand why this latest correction is necessary. If a distant luminous body is broadcasting 1000 million quanta from a certain unit area of its surface each second, and if only 900 million quanta reach us, it is inevitable that the photographic image which the 900 make will be fainter than the image which the full 1000 would have made. Thus, the image we receive is less luminous than it should be to represent the actual brightness of the galaxy. Since faintness is the criterion of distance, and since the extent of the red shift increases directly with the distance of the object, it follows that we have been rating the remote galaxies as more distant than they really are. Assuredly, then, the correction for the number

effect must be made. And so we accept it, altering the brightness of our objects, and changing their distances accordingly.

What follows is a shrinkage of our scale. The correction draws the galaxies nearer to us, the more remote the object the more considerable is the reduction of its distance, and thus we attain a corrected density which assumes a different arrangement from the comfortable reassuring common-sense density of uniform distribution.

Thus corrected, our astronomical photographs disclose a curiously unbalanced world. The distribution of matter grows more dense with distance, the spacing between the galaxies dwindles, the emptiness fills in, the star systems increasingly gang closer and closer together—a strange, lawless, unaccountable Universe which no authority is willing to accept.

3

Dr. Hubble points out that the fantastic picture may be avoided, and the results interpreted within the theory of the expanding Universe, if we assume that space is sharply curved. The increased crowding of the galaxies with distance may then be explained as a relativity effect, the curvature of space causing the galaxies to appear more concentrated than they really are.

But such an assumption involves other considerations. This idea of curved space is quite fundamental to the theory of relativity; for relativity holds that space indeed is curved by the gravitational influence of the matter which it contains, and that the greater the mass of the matter the greater is the curvature. If there were no matter, there would be no curvature. The fact of curvature indicates the presence of matter. And from the degree of curvature the density of space, *i.e.*, its content of matter, may be computed. Hubble calculates that if the total matter of the Universe be assumed to average the one-

hundred million million million millionth (10^{-26}) part of a gram to each cubic centimeter of space, then the curvature would be such that the red shift would operate about as we see it, the apparent increase of crowding with distance would be resolved as an illusion and the distribution made uniform again, and thus the strange picture would be reconciled.

Although Hubble's calculated density may seem to be a very small fraction, it is really an enormous increase over the densities previously assumed. For such a density to be actual, it is necessary that the Universe contain vast quantities of nonluminous material. Indeed, by his reckoning, the invisible dark stuff must be a thousandfold more than the luminous stuff of stars and nebulae which we see as making up the galaxies. We know that there is nonluminous material in the spaces between the stars. Several years ago thin mists of sodium and calcium atoms were detected floating through the interstellar wastes, and recently Walter S. Adams and Theodore Dunham discovered titanium atoms also among these diffuse wanderers. We know of yet denser clouds of nonluminous material—they have been sighted as a fog of dust obscuring the central girdle of our Milky Way and appearing as obscuring belts encircling some of the outside galaxies. But this dark dust cannot account for the huge surplus of mass that is needed to curve space according to the new computation, for the dust very markedly obscures light. Since the light from the distant galaxies gets through without noticeable obscuration, the unknown material that we seek in the darkness must be of such size and in such condition that it does not absorb light. Conceivably the nonluminous matter may exist in concentrated form, in chunks or large fragments; and of course there are the highly condensed black dwarf stars which we are just beginning to recognize and which may exist in large numbers. It is not impossible that the invisible contents of space may outweigh the visible a thousandfold.

All these assumptions might be acceptable to the expansionists, but for one item. Hubble finds that the radius of curvature of a world as dense as he has calculated would be a matter of a mere 470 million light-years. And that is almost inconceivably small. In 1934, guided by the actual observations of the distribution of galaxies in representative samplings of space, Hubble estimated the radius to be 3000 million light-years. It is this sharp reduction of the scale, this shrinkage to about a sixth its former value, that makes the 1936 findings so astounding to all cosmologists and so challenging to the relativists.

Does Hubble's small-scale model represent the real structure of the Universe? Not necessarily—he has proposed an alternative solution—but *if* we accept the red shift as a result of receding motion, it is the only model that fits the conditions. To quote Dr. Hubble: "If red shifts are velocity shifts, the model is closed, small, and dense. It is rapidly expanding, but over a long period the rate of expansion has been rapidly diminishing. Existing instruments (the 100-inch telescope, for example) range through a considerable fraction of past time since the expansion began."

In other words, if the red shift means expansion, the Universe must be a very small system of which we have already glimpsed a large part.

But suppose the red shift means something other than a velocity. Suppose we abandon the idea that this curious behavior of light, which tells so much of the motion of our stars, is giving us the same sort of information regarding the motions of outside galaxies. Grant that we have no certain evidence of recession of these remote bodies. Then that third correction—the number effect, which caused all this seeming nonsense—becomes unnecessary. And the uniform distribution which we found at the end of our first two sets of corrections is restored. With no clue to the reason for the red shift, we can no longer cite any observa-

tional evidence for expansion, we can find no trace of curvature, no limitation of space, no restriction of the time scale. "The sample, it seems, is too small to indicate the type of Universe we inhabit." For all we know, then, the Universe may be infinite in extent, ageless in time, and subject to "some unknown principle of nature" which eternally shifts fossil light toward the red.

4

These two solutions have been proposed by Dr. Hubble as alternatives. And while he is not committed to either of them, he admits that in the present state of knowledge the second solution seems the more promising approach to the problem. The expanding model, with its small, dense, closed Universe, involves many improbabilities and seems less plausible than the suggestion of an unknown immensity of which we have sounded only an insignificant sample and in which there is yet to be discovered the "unknown principle" which mysteriously reddens our skies.

Other authorities also indicate a tentative preference for the second solution, but with a reasonable caution. In the opinion of H. P. Robertson, as expressed in a report to the Physical Colloquium at Princeton discussing Dr. Hubble's preliminary announcement, the second alternative would seem easier to reconcile with the facts now before us—*provided there were any experimental or theoretical grounds for believing that light is subject to fatigue.* The great difficulty, of course, is that no such grounds are known. But apart from this, and quite independent of what the red shift may finally prove to mean, the general theory of relativity stands established by many experimental tests. As long as relativity is accepted as correct, and as long as the evidence points to a sensibly uniform distribution of matter in space, one is necessarily led to one model or another of the several types of "expanding universes" broached by Alexander Friedmann on theoretical considera-

tions in 1922. This was before the strong evidence of the red shift had accumulated; indeed, Friedmann arrived at his conclusions without knowledge of the red shifts. We may therefore say that a world picture which was derived from sound theory in 1922, without the assistance of observational evidence, and later was supposedly confirmed by the discovery of the evidence of the red shift, does not necessarily fall when the assurance of the evidence is questioned.

One of the details found by Hubble in his first alternative —the small, dense, closed model, with the red shifts accepted as measures of velocity—is that the rate of expansion has been rapidly slowing down. From the data given in Hubble's preliminary report to the National Academy of Sciences, Robertson has derived a tentative estimate that the present age of this small-scale Universe is probably less than 1000 million years. This is a cramped time-scale for a world in which the Earth is rated as thousands of millions of years old and the stars as yet older.

If the smallness, youthfulness, and other anomalies of this dense closed model compel us to abandon our customary interpretation of the red shift, we have left at present no way of choosing among the various proposed types of expanding universes—or even between them and the static universe first suggested by Einstein in 1917. The dilemma, therefore, is more complicated than appears at first sight in Dr. Hubble's two alternatives. If we reject the curiously small, youthful, closed model, with its remarkably high density of matter, to accept a postulate of tired light, we have to accept also the idea that this light is propagated in a Universe which may be expanding in any one of several ways without our being able to test it by any physical means now at our disposal.

But present limitations may be springboards for future accomplishments. The 200-inch telescope mirror is in process of being ground in Pasadena. Its massive metal mounting and mechanism, precise and responsive to the

hundredth of an inch, is in process of construction in Philadelphia. Its foundations are already being prepared on Mount Palomar. The great mirror will have the light-gathering power of 1,000,000 human eyes. It should penetrate more than 1000 million light-years. By 1940 it will sweep the skies, surely to break through many barriers—possibly to push out into a vaster world than even our imaginations dream—or, it may be, to prove that the small, dense, closed world is indeed the Whole.

Meanwhile, some penetrating thrust of theory, some adroit mathematical countermarch, may resolve the difficulty in advance of the instrument.

Chapter V · THE ENCIRCLING DARKNESS

I feel and seek the light I cannot see.

—S. T. COLERIDGE, IL ZAPOLYA

INSTRUMENTS such as the 100-inch telescope now on Mount Wilson, or the 200-inch now under construction for Mount Palomar, might prove to be rather embarrassing "white elephants" were it not for the auxiliary equipment which extends the reach of the telescopes and gives increased effectiveness and permanency to their seeing. We need more than telescopes for our ventures into the darkness.

All that a telescope can do is to concentrate light. The great mirrors spread a concave glass disk as a trap to catch rays, and the curve of the mirror and the shape and arrangement of the accessory optical parts are such as to concentrate all the captured light into a very small area or point. The eye of the astronomer then sees what it would see if its pupil were as large as the mirror. It sees stars and nebulae that were invisible to the naked eye. And it sees them, not because the telescope has magnified them, but because it has intercepted and collected and concentrated a large enough quantity of their light. A certain minimum number of quanta are necessary for seeing. The number varies for each color or wave length, but even for the most

energetic blue light the requirement is many thousands per second. Until at least this number is being delivered to the retina in each unit of time, there can be no sensible activation of the optic nerve, no image received by the brain, no vision.

The most distant objects measured by Dr. Hubble and his associates in their recent survey of the distribution of outside star systems are faint galaxies rated as of the 21½ magnitude. That is to say, each of these immense star swarms shines with a brightness about equal to that of a 21½-magnitude star. And the apparent luminosity of a star of this magnitude is that of a candle viewed with the unaided eye at a distance of 8575 miles. Hubble estimates the distance to these galaxies as about 500 million light-years. Their light is so scant that the entire surface of the 100-inch mirror intercepts only about 500 of their quanta per second. This is far below the minimum requirements of human vision; many thousands per second would be necessary for the optic nerve to catch even the beginning of an image. So, even with the help of the largest telescope on Earth, the eye of a man is unable to see an object of the 21½ magnitude.

It is by the aid of photography that these faint luminaries have been made to show themselves, and then only by prolonged exposures. Seven years ago exposures of 40 hours were common practice; a single photograph of a spectrum would represent several nights of slow accretion of the image on the plate. Today, with the more sensitive emulsions now available and with the added help of the more reflective aluminum surfaces for mirrors and of other optical aids, an exposure of 3 hours through the 100-inch telescope is sufficient to reach these remote systems.

This ability of the photographic emulsion to record faint images by a cumulative process is not the only reason why the large telescopes have become primarily the apertures and optical systems of powerful cameras and why the

modern astronomer has become an expert photographer. There are other reasons—many advantages a permanent photographic record has over a passing visual view. With the introduction of motion-picture technique, such as that already begun at the University of Michigan, photography may attain a superiority over the eye even in the observation of rapidly changing features of the sky scene. But a yet more fundamental and clinching argument is the fact that photography is sensitive to invisible rays of which the eye is not aware. The inanimate but responsive chemical mechanisms of the photographic plate can "feel and seek the light I cannot see."

I

That there is a light the human eye cannot see was beautifully demonstrated at the Kodak Research Laboratories in Rochester one morning. A group of industrial executives gathered from various cities had come here to see some of the wonders of modern photography, and were waiting in a little theater on the top floor of the six-story laboratory building. This theater is in itself a unique institution, completely equipped with every photographic and lighting facility, a versatile projection room for sound-movie films, an outpost and testing ground for photography, a place where light is explored, experimented with, put through its paces. The group of visitors were seated here when a voice from the stage announced, "Hold steady a moment, we are going to take your picture," and the lights were switched off.

"In the dark?" A man held up his hand 2 feet from his face and could not see the faintest outline of it.

There was a click, a second of midnight silence, then the shutter gave another click and the lights were turned on again. Twenty minutes later damp prints of the photograph were being passed among the astonished visitors. Each

saw himself as the invisible camera eye had spied him in the blackness.

It was very strange, especially to those who had been schooled from their earliest picture-taking days in the necessity of good lighting for good photography. Here, apparently, was a kind of photography that was able to dispense with light.

The feat was no trick stunt of the magic theater, however; for a few weeks later Captain Albert W. Stevens, photographer of the United States Army Air Corps, took his aerial camera on a flight above California and showed what could be done in the open. At a height of 23,000 feet he pointed his lens due north, opened the shutter, and let the camera register what it saw. Ordinarily one would expect a blur, for the panorama was wrapped in haze, and eyesight could penetrate only a few meager miles. But when the plate was developed Captain Stevens found that he had taken a picture of the snow-clad peak of Mount Shasta 331 miles away.

What a contrast with that first portrait taken nearly a century ago on the roof of New York University—when the "subject" was compelled to daub her face with white powder and sit motionless several minutes in the bright sunlight while the daguerreotype slowly built in its image!

To penetrate 25 feet of theatrical darkness or 331 miles of atmospheric haze, the problem is essentially the same: a problem in sensitivity. The noses of dogs are more sensitive than the noses of men; they register smells which are beyond human apprehension. Similarly with these photographic plates; they are more receptive than the optic nerve, and register light waves which are beyond human perception.

So there were light waves in the dark theater?

"Plenty of them," answered C. E. K. Mees, director of the laboratories and master of this unique show. "But," he quickly explained, "the light was of an invisible quality—

that is to say, of a wave length so long that it is beyond human seeing." All the photographers did was to coat the photographic plate with a thin film of chemical emulsion that is sensitive to these rays, and expose that in the camera of the darkened theater. At the same time, certain hidden electric lamps flooded the room with invisible heat radiation. These rays are effective on this kind of sensitized plate in much the same way that the visible rays of sunlight are effective on ordinary photographic plates and films.

To approach our problem systematically let us recall a few familiar facts. When sunlight passes through a prism it emerges in the banded rainbow pattern of the spectrum, the well-known series of colors ranging from the deep blue of violet to the deep red of glowing iron, together with innumerable intermediate tints that shade from one primary color into the next one. But this seemingly infinite variety is really quite finite. Each color is the signal of a certain wave length. Beyond the violet at one side of the rainbow is a considerable series of other vibrations, each of shorter wave length than its predecessor. Similarly, at the other side, beyond the red, are other vibrations in a lengthy sequence, each of longer and yet longer wave length. To these shorter vibrations beyond the violet and these longer ones beyond the red, the eye is stone-blind.

The wave length of deep blue light is about 15 millionths of an inch. This is the measured distance from one wave crest to the next of the kind of vibration that makes an eye see what we call blue. The wave length of red light is just about double that of the blue—30 millionths of an inch.

A red-hot poker, then, is broadcasting on a wave length of 30 millionths of an inch. But when it is heated more and glows a deep blue, it is broadcasting on a wave length of 15 millionths of an inch. We are assuming an ideal poker that does not melt, no matter how high you heat it. Be-

tween the two wave lengths lies all the visibility of the world.

Suppose we allow the red-hot poker to cool until it no longer glows. In the dark we cannot see the poker, but it has not ceased to broadcast radiant energy, for we still feel its heat beating against us through space. It has merely shifted to a longer wave length and is now radiating a wave perhaps double that of the red. Presently, as it cools more, it will shift to yet longer vibrations; and presumably it will continue to radiate until its molecular motions approach the inactive stage of absolute zero temperature.

The problem of seeing, therefore, essentially is one of tuning in. If we could tune our eyes, as we do our radio sets, to receive waves longer than 30 millionths of an inch, we could see the infra-red. Then the cooling poker would be clearly discernable in the dark, a desert would glow at night in the "light" of its hot sands, midnight in any land would be luminous with the infra-red rays of the warm Earth.

There is no darkness in any absolute sense. The deepest mine is aglow with the rays generated by its warm rocks and metals—if we could but see them. The blackness of the abyss of interstellar space is shot through and through from every direction with innumerable darts of radiation. Man, so weak of eyesight that he can directly apprehend only a sixtieth part of the range of radiant energy that we now know, has yet discovered that wide range. By indirect chemical and physical means he has contrived to capture the unseen, and to convert its invisible motions into visible messages which his eyes can see and—at least, in part—can decode and understand. Photography and electronics are two principal techniques of this advance.

2

Modern photography, like almost every other attainment of science, is the result of a many-sided collaboration.

Optical experts, physicists, mechanicians, and divers other precisionists had a hand in the new development, but the rapid advance in the photography of invisible radiation is largely the work of chemists experimenting with new combinations of dyes.

The ordinary photographic plate or film is even more limited in its color range than the human eye, for it can "see" of the visible spectrum only violet, indigo, and blue light. Objects of a green, yellow, orange, or red color affect such photographic emulsions as though they were dark, which means that they do not affect them at all. In 1873, H. W. Vogel, a Berlin chemist, noticed that some dry plates in his possession showed a sensitivity to green light. He investigated, and found that a certain dye, which had been mixed in the emulsion to prevent spreading of the image by halation, was responsible for the added sensitivity. Vogel tried other dyes and from them obtained similar effects, and out of his pioneering came the discovery that when a dye acts as a sensitizer, the color for which it is effective is the color which the dye itself absorbs. For example, the dyes which sensitized the emulsion for green light were each a substance that quite apart from the photographic mixture was itself an absorber of green light. "This fundamental relationship underlies all work on sensitizing," points out Dr. Mees, "and it is worthy of attention that Vogel grasped this truth immediately in spite of the fact that his emulsions were very slow, his dyes probably impure and, at best, weak sensitizers, and his apparatus primitive."

Although the principle was discovered so early, more than 30 years were to pass before photographic plates responsive to the entire range of visible light became available. By 1904 several isocyanine dyes had been found to extend photographic sensitivity through the green, yellow, and orange regions. In 1905 came the synthesis of a new dye, pinacyanol, which carried the conquest of the chemist

over the entire region of red and even a little beyond into the invisible infra-red. Astronomers and physicists immediately began to use the new tool.

But they yearned to photograph more than the visible. It was known that the Sun broadcasts heat as well as light, and the Sun explorers were eager to have a photographic record of this heat spectrum for the news that it might bring. Away back in the later years of the nineteenth century the English investigator Abney had succeeded in getting a few such records, but his plates were extremely difficult to make and use. The first substantial approach to the problem was provided by the pinacyanol dye, for, as I have said, this German dye showed a sensitivity to a few of the heat rays just beyond the deep red at which visibility ends. In 1910 R. W. Wood at Johns Hopkins University made good use of this opportunity. He photographed sunlit landscapes on plates sensitized with pinacyanol. Before exposing the plates he fitted a red glass filter over the lens so that all the wave lengths of visible light would be stopped and only those of the invisible infra-red admitted. These early infra-red landscapes resemble our modern ones quite closely; they show the same striking contrast of dark sky and light clouds, the same brilliant "whiteness" of foliage. But there is this significant difference between Dr. Wood's photographs and our modern ones: he found it necessary to expose the plate about 5 minutes in each instance, whereas the same results are obtained today in a fiftieth of a second.

The modern advance is measured not only by the quicker response of the new dyes, as indicated by the speeding up of exposure time, but also by the wider range of invisible wave lengths now subject to photography. I have spoken of wave lengths in terms of fractions of an inch. But measurements of these small-scale dimensions in fractions of large-scale units is awkward, and many years ago the physicists adopted a unit known as the angstrom—so

named in honor of A. J. Ångström, the distinguished Swedish spectroscopist. An angstrom is the one hundred-millionth part of a centimeter. The shortest wave of visible light (blue end of the spectrum) measures 4000 angstroms, the longest wave of red measures 7000 angstroms. Dr. Wood, with his plate sensitized by pinacyanol, was able to photograph out to about 7100 angstroms. Since by the filter he had cut out all vibrations shorter than 7000, his photography in 1910 was confined to the narrow region of vibrations between 7000 and 7100.

The first substantial advance came about a decade later. E. Q. Adams and H. L. Haller, experimenting at the Bureau of Chemistry in Washington in 1919, discovered a new dye which sensitized very powerfully for infra-red radiation out to 8000 angstroms. This synthetic compound was named kryptocyanine. I should add, to make the record clear, that an earlier dye known as dicyanine had been discovered in Germany and found effective as a sensitizer for this same infra-red region, and even beyond. But dicyanine was so unstable, so likely to break down suddenly and fog the emulsions, that few scientists used it. The new kryptocyanine, on the other hand, was quite stable, easy to handle, and could be added to a photographic emulsion without danger of rapid deterioration. It was so powerful that one part of the dye in half a million parts of the emulsion was sufficient to give the maximum sensitization.

By means of this new compound the chemical conquistadors of light pushed their photographic domain out to cover an infra-red range ten times greater than that Dr. Wood had photographed. But it was only a beginning of the swift advance of the next decade. In 1925, H. T. Clarke was preparing some kryptocyanine in the Kodak Research Laboratories when he noticed that the condensation resulted not only in the expected product, but also in a less soluble dye which separated out. By further experiment

Dr. Clarke prepared the new dye as the main product. Tests showed that this neocyanine, as the discoverer named his accidental find, was sensitive out to 9000 angstroms. Later trials revealed that a still farther reach of sensitivity can be given to neocyanine by treating it with ammonia. Using plates so treated, H. D. Babcock at Mount Wilson Observatory photographed the solar spectrum as far as 11,634 angstroms.

But this is not our limit. In 1932 a new group of dyes began to issue from the laboratories of the molecule builders, refabricated compounds which were immediately tested by the photographic chemists and found to be uncommonly absorptive of heat rays. Some were absorptive of one band of wave lengths, some of another, and the one which carried this absorptive quality to the farthest extreme was the dye called xenocyanine. It was a very flighty compound, could be prepared and used only at low temperatures, and the emulsions were effective only if used shortly after making. Despite these conditions, some helpful results were obtained with the use of this temperamental chemical. But research pushed on. Soon other compounds were found to possess the heat-absorptive quality, and lately some have been obtained which are more stable than xenocyanine. The photographic researchers have given up trying to find descriptive names for the new dyes, and these latest compounds are known as "class *Z* sensitizing." W. F. Meggers and C. C. Kiess, at the National Bureau of Standards, have used plates sensitized with this new material to extend our standards beyond 12,000 angstroms wave length. Babcock, again using the great solar spectrograph at Mount Wilson, has found the new sensitizer useful in carrying this survey of the Sun's spectrum out to 13,536 angstroms.

3

A characteristic of infra-red waves of radiation is their ability to get through haze and other conglomerations of

atmosphere. The shorter wave lengths are less successful, and even in a clear sky some are stopped. Indeed the fact that the sky looks blue is evidence that much of the blue sunlight of short wave length is scattered. The blue waves are scattered by reason of their collisions with air molecules and invisible dust motes of the atmosphere, and the longer the wave lengths the less susceptible are they to this scattering effect. When the sky is thick with haze, caused by dust motes afloat in the air, the Sun may appear red as at sunset, an effect caused by the scattering of most of the wave lengths shorter than red. As the haze thickens with increased density of dust or increasing distance to be penetrated, or as moisture collects on the particles and deepens the haze to a slight cloud or slight fog, even the reddest wave lengths may be turned aside and scattered. Then the Sun is no longer visible as an image, only the gray indistinctness of neutral or scattered light remains. It is at this stage that the infra-red waves become indispensable, if we are curious about what lies beyond the haze. For the infra-red vibrations, of slower frequency and longer wave length, are large enough to spill over the atmospheric particles and pulse through the haze for long distances, and write their invisible messages as photographic images on our plates—provided the plates are sensitized with the right dyes.

It must not be inferred that infra-red photography is effective through all densities of mist. The new dyes can be used to increase visibility through haze, and even through a light fog or cloud, but the infra-red rays that penetrate ordinary fog densities are of wave lengths too long for our present photographic stratagems. The reach that we have won, however, is of very great practical importance.

When the first kryptocyanine plates were received at Lick Observatory on Mount Hamilton, W. H. Wright there thought he would try the new photography on a terrestrial scene. He pointed his camera at the Yosemite Valley. The valley lies 130 miles from Mount Hamilton, hidden

behind the haze of that long stretch of air, vague and fuzzy on even the clearest days. In the infra-red photographs the details came out with remarkable sharpness, and at once it was recognized that here was a powerful practical tool for penetrating atmospheric opacities.

If a distant scene could be photographed from a mountaintop, as Dr. Wright had demonstrated, why not from a moving airplane? Captain Stevens was one of the first to try that, and his photograph of Mount Shasta is only one of a series of successful long-distance shots. His first major attempt of this kind was directed at Mount Rainier. It is said that on that flight his pilot was rather mystified by the captain's actions. He could not understand why, long after the mountain had disappeared from sight, the captain pointed his camera in that direction—apparently at nothing. The pilot was even more astonished a few hours later, when the negative was developed and printed, and he saw the clear photograph of a wide stretch of mountains and valleys, dotted with familiar peaks: the Three Sisters, Three-fingered Jack, Mount Jefferson, Mount Hood, and farthest of all, the white spire of Mount Rainier. This last had been photographed through 227 miles.

Later, on a flight in South America, Captain Stevens obtained a sharp photograph of Mount Aconcagua, in the Andes, at a distance of 310 miles. This picture is remarkable in many respects. It shows the line of haze over the South American pampas as curved, corresponding to the curvature of the Earth's surface. Subsequently, from the stratosphere balloon Explorer II, taking an oblique photograph at a height of more than 13 miles, Stevens got an even more impressive record of the curvature. These results suggest that some day some higher flying aeronaut or rocketeer may capture on a sensitive film the vast bend of our planetary edge in yet more distant perspective and show an appreciable segment of our globe. "There is no limit to the distance over which objects can now be photographed,

except that imposed by their size and by the curvature of the Earth," says Dr. Walter Clark.

Infra-red photographs appear weird in some of their details, and this is because certain substances reflect and transmit the invisible rays much more freely than they do our familiar visible light. In an infra-red photograph of a landscape, for example, the foliage shows an intense brilliancy as though it were powdered with snow. This appearance is explained by the presence of chlorophyll, the green coloring matter of the leaves, which has a very high reflectability for the infra-red. In an exposure of an outdoor scene, more of the invisible light is reflected by the leaves than by other objects, consequently more reaches the photograph from the leaves than from other objects, and their images are made to appear brighter by contrast.

It has been discovered that infra-red radiation penetrates the skin and some distance into the underlying tissues of the human body. The network of skin and tissues scatters the rays, and the photographed result is a white effect on the infra-red print. If there is a blood vessel under the skin, this different substance interferes with the scattering, and the blood vessel photographs dark against the lighter background of skin and tissues. Thus many details of underlying blood vessels which are quite hidden to the eye are brought to view by the penetrating rays. Varicose veins, capillary congestions, and similar disarrangements show up in infra-red prints, and the possibility of using this new photography as an aid to medical diagnosis seems favorable. Already botanists have found that certain diseases of plants may be detected in their early stages by infra-red photography of the foliage.

There is a treasured copy of De Bry's *Voyages* in the Huntington Library at San Marino, California, but the book is sadly defaced. It seems that certain of its passages offended an ecclesiastical censor back in 1632, and so he blotted them out with thick layers of black ink. The

Library authorities tried various means to circumvent the censor without endangering the book, but all these efforts were unsuccessful until they heard of the infra-red photography that Mount Wilson astronomers were using to get through the obscuring clouds of planets. Might it not also penetrate the censor's ink? Dr. L. Bendikson borrowed some of the infra-red plates from the observatory, and was delighted to find that in photographs made with the invisible light the hidden passages came clearly to view. It was this quality of selective transparency that made such a result possible; for if the two inks had responded similarly to the infra-red, or even if the outer ink had possessed less transparency than that of the printing, the censor might still be triumphant.

Each of these practical uses of the new sensitivity suggests other possibilities, and it seems likely that infra-red photography may in time have as many and as different applications as x-ray photography has attained in its 40 years. The astronomers have made more use of the technique than any other group—but perhaps their results would not meet the tests of "practicality" with which some men, as Joseph Conrad has said, starve their imaginations to feed their bodies. Have a care, though, how you pronounce on futures in these realms. Some day some rocketing real estate magnate, looking for other planets to stake out and subdivide for development, may find it quite important to know whether Venus has a better atmosphere than Mars, and what sort of arrangements may be found in Jupiter and Saturn. Already the astronomers have some reliable data on these questions, acquired by means of infra-red photography.

4

Most of the astronomical explorations with infra-red have been made through the spectroscope. That is to say, the direct image of the heavenly body is not photographed,

but its light is passed through a prism or reflected from a diffraction grating, and the resulting spectrum is photographed. Many of the lines in the spectrum are far out in the invisible regions on either side of the rainbow, and for some elements and compounds these lines of invisible light are the only significant signals. If they are far out in the ultra-violet, they are lost in the upper air where a high layer of ozone absorbs all the ultra-violet except for a narrow region near the visible. Thus, most of the ultraviolet light is filtered out of the sunshine by this gaseous layer and never reaches us. But if the signals are lines of the infra-red, they are now an open book, thanks to the facility of the new photography. The presence of phosphorus in the Sun was recently discovered in this way, by the photographing of infra-red phosphorus lines in the solar spectrum. And similarly astronomers have been exploring the atmospheres of the planets.

Planets, of course, have no light of their own. Each shines by reflected sunlight. But it so happens that when the light of the Sun falls upon an envelope of gas, such as the atmosphere surrounding a planet, the atoms and molecules of the atmosphere absorb certain wave lengths of the sunlight according to their peculiar affinities. The result of this selective absorption is to add certain dark lines to the spectrum, and these then show up by contrast with the spectrum of direct sunlight. The dark absorption lines added by the planetary atmosphere become clues to the make-up of the atmosphere. In this way it was recently discovered at Mount Wilson Observatory that the atmosphere of Venus is dense with carbon dioxide gas, its upper layers containing 10,000 times as much carbon dioxide as is in the whole atmosphere of the Earth, that the atmospheres of Jupiter and Saturn contain ammonia, and that the amount of oxygen in the atmosphere of Mars is not more than ¼ of 1 per cent of the Earth's atmospheric oxygen. Similar studies at Lowell Observatory have re-

vealed the presence of marsh gas (methane) in the atmospheres of Jupiter and Saturn. These findings are not encouraging to the hypothesis of life on the planets. We know no form of animal life that can breathe ammonia and methane, or that could get along on the meager oxygen available on Mars. The presence of so much carbon dioxide on Venus might argue an environment favorable to plant life were it not for the fact that Venus is perpetually shrouded in dense clouds. These completely blanket it from the visible rays which on our Earth are necessary to vegetation.

The presence of ammonia and methane in the atmosphere of the two largest planets, Jupiter and Saturn, raises some nice speculations of chemical origins and evolution which a chemist, Walter Clark, recently discussed. "Ammonia," as Dr. Clark pointed out, "is a very reactive gas, consisting of nitrogen saturated with hydrogen. Methane, less reactive than ammonia, and familiar as 'marsh gas,' consists of carbon saturated with hydrogen. Both gases are stable. It is possible that collisions of atoms in the atmospheres of the planets have continued over vast periods of time, until eventually these most stable constituents have survived. It has been suggested that methane and ammonia are just the gases which would be expected to form if a mass of gas, having a composition like the atmosphere of the Sun, were allowed to cool slowly to a very low temperature." The present temperature of Jupiter and Saturn is rated at about 180° below zero Fahrenheit.

5

Thus far, our story of the new photography has emphasized attainments with infra-red. Ultra-violet radiation is somewhat less useful to astronomers, because of the atmospheric absorption mentioned on a foregoing page. But these short waves beyond the violet have done wonders for the physicist. They have brought news of the structure of

atoms and have provided tools for probing into the behavior of atomic parts. Just as the temperature or energy state determines whether the iron atoms of the poker shall broadcast blue light, or red light, or invisible infra-red, so does it ordain the invisible radiations at the other side of the spectrum. An atom excited to a certain energy state vibrates visible light. Excited to a higher energy state, it gives off ultra-violet. Still higher, its output is an x-ray. And when the central citadel, the nucleus, is in a state of agitation, its radiation comes forth in the yet shorter wave known as a gamma ray. All these waves beyond the violet are potent photographically. Indeed, it was the accidental fogging of some plates in his laboratory that prompted Röntgen to search for and find the x-rays. Similarly, it was by means of photography that Becquerel discovered the gamma rays.

The shortest wave of visible light measures, as we have seen, about 4000 angstroms. Just beyond this extreme blue end of the spectrum the ultra-violet begins, and its region extends through shorter and yet shorter vibrations until a wave length of about 100 angstroms is reached. The invisible regions overlap, there is no sharp boundary between the shortest ultra-violet rays and the longest x-rays, nor between x-rays and gamma rays. But in general it is accepted that the sequence from about 100 angstroms to about 1/100 angstrom is the realm of x-rays, and from 1/100 angstrom down is that of gamma rays.

Most x-rays, and all gamma rays, are of such short wave length that they can penetrate solid materials, like flesh, or even sheets of metal, darting their way through the relatively enormous open spaces between atoms and atomic parts. Also, they are so packed with energy that in a collision they are able to knock parts out of atoms. It is plain to see that if we have a means of detecting the mutilation of atoms we should thereby have a means of detecting the presence of x-rays and gamma rays. Such

detectors have been made—electroscopes and ionization chambers are examples—and with these electronic devices it is quite possible to "see and feel" the invisible short-wave light of x-rays and gamma rays even without a photographic plate. Refinements of these devices have enabled the investigator to measure the energy of the rays. And since wave length is related to energy in a very definite way—the higher the energy, the shorter the wave length—it is possible from these measurements to ascertain the energy and wave length of unknown rays; such unknowns, for example, as cosmic rays, the mysterious bombardment that continually beats upon our Earth and all its cargo.

The penetrating power of some of this cosmic bombardment is so great, its load of energy is so tremendous, that if the thing is a species of light its wave length must be thousands of times shorter than any known gamma ray. If the thing is a charged particle of matter, its velocity must be enormously high. Science is still groping for knowledge of the origin and nature of the bombardment, but the story of its discovery and continued pursuit is one of the most fascinating in the annals of modern research.

Chapter VI · THE COSMIC BOMBARDMENT

I cannot tell you how it was;
But this I know: it came to pass.
—CHRISTINA ROSSETTI, MAY

THE electroscopes began it. They would not behave—or they could not. It became necessary to find out what was ailing them, whether an electroscope was really the sober law-abiding trustee and holder of electricity it was supposed to be, or something else quite different. Out of such detective work a new presence was discovered, strange, invisible, but superlatively active demons of energy—the ubiquitous cosmic rays.

Ubiquitous, says my dictionary, means "everywhere present." That describes cosmic rays. They beat upon the Earth from every direction. Nothing is exempt from their toll. No creature is immune to their prying darts. While you have been reading these paragraphs several hundred cosmic rays have plowed through your body.

Atoms of metals are hammered into excitation and eruption by their impacts, and what may happen to the lighter atoms of flesh and blood we can only conjecture. Cosmic rays may be benefactors, the aiders and abettors of life, or they may be destroyers, the insidious enemy of all that breathe, or they may be of no biological consequence—we

do not know. The speculation, however, gives to the mysterious radiation a temptingly personal aspect. It provides for our table talk a new and tantalizing *if.* Instead of blaming our tempers and other idiosyncrasies on the heat or the humidity or the depression, we may find in the cosmic rays a new alibi. Possibly evolution is hastened by the incessant bombardment. The idiot may be the casualty of some cosmic-ray collision with the living atoms of heredity, and similarly the genius may be the accidental outcome of a more fortunate mutilation.

You may wonder that this bombardment could go on for untold ages, and only yesterday be discovered. Our knowledge of cosmic rays is a thing of the twentieth century; it dates back hardly 25 years; and, as I have said, the electroscopes began it.

I

A cat's back is a familiar form of electroscope. Stroke its fur and you charge it with electricity. The hairs of the fur stand on end with the charge, but bring the tip of your finger near, there is a sudden crackling and the flash of a spark as the load passes off and is dissipated, while the erect hairs settle down. But cats are temperamental, and for reliable laboratory service the pioneer electricians invented the gold-leaf electroscope. Here a thin strip of gold-foil substitutes for the fur and when charged stands out from its insulated support, erect and bristling with electrical potential.

It was this gold-leaf electroscope that the early explorers of radium turned to as an aid to their researches. Radium is continually shooting out its gamma rays; these rays smash the air particles they collide with, thus electrifying the particles and causing them to flow to the gold leaf and discharge it. The radiologists found that the time required for the gold leaf to settle down was an index to the intensity of the radium rays.

But was it a precise indicator? If they could be sure that the discharge was caused solely by the electrified particles actuated by the radium, and that no other influence was affecting the apparatus, then they could rate the intensity of the gamma rays directly in terms of the behavior of the gold leaf.

So tests were made. An electroscope was completely insulated, and isolated from all known sources of electrification. Then it was charged. Theoretically, it ought to hold that charge indefinitely. But after a few hours the gold leaf began to droop, and eventually its charge had disappeared. Trial after trial demonstrated that no amount of insulation or isolation would stop this strange loss. It was called "the natural leakage," and physicists were able to compute its magnitude and allow for it. But computing an unknown does not explain it, and many were the speculations on this odd behavior.

A favorite theory attributed the natural leakage to the natural radioactivity of the Earth. The rocks and soil possess their small quota of radium and other radioactive metals, even the air carries finely attenuated amounts of radon gas, and the radiations given off by the exploding atoms of these elements might account for the leak. But 3 inches of lead will stop the most powerful known gamma ray; so an electroscope was sheathed in leaden plates several inches thick, in addition to the protection of its insulation. The leakage was slowed down somewhat, but it continued as before. A group of Canadian experimenters sledded an electroscope far out onto the frozen surface of Lake Ontario. Six feet of water will stop all radium rays; here the thickness of water and ice between the instrument and the rocks of the Earth was several hundred feet, but this unusual protection did not avail. The charged gold leaf slowly settled down.

How high up in the air would this strange influence reach? Father Theodore Wulf, a Jesuit priest in Paris, carried an

electroscope to the top of the Eiffel Tower and found that it continued to discharge at that height, 984 feet. Then, in Switzerland, A. Gockel loaded an electroscope into the basket of a balloon and found that at the 3-mile level the gold leaf still leaked. Certain observations prompted him to suggest that the effect might be expected to increase with altitude.

Stimulated by these experiments, the German physicist V. F. Hess engaged a larger balloon and attained a higher altitude. And Hess came down with an amazing report of fulfillment of Gockel's prediction. Not only did the electroscope continue to discharge at the ceiling of his flight, but the discharge steadily increased as he went up. Hess concluded that the invisible influence "enters our atmosphere from above."

These reports were disquieting to the custodians of knowledge. Many doubted the accuracy of the experiments. Another German, W. Kolhörster, determined to make a definitive test. He procured a very large balloon, installed an extremely sensitive electroscope, and ascended to a height of nearly 6 miles. Kolhörster's more precise measurement over a much longer range of altitude completely confirmed Hess's result. There could be no doubt about it: the higher the balloon rose, the more rapidly did the charge on the electroscope ooze away.

The World War arrived shortly after these events, and further investigation was set aside by the more insistent demands of the Great Madness. Perhaps if any of the military minds had been aware of the tremendous energies resident in cosmic rays, they might have been captivated by the thought of possibly harnessing the rays for war purposes, and research might have advanced still farther. For while the total amount of heat brought to the Earth by cosmic rays is less than that of starlight, the energy of the individual ray is unbelievably great. Thus, when a cannon ball is moving at its greatest velocity, the energy

of its motion averages less than one electron-volt per atom—but cosmic-ray encounters recently photographed show that some of the rays are endowed with energies of 20,000 million electron-volts and more. Imagine cosmic rays concentrated into a beam!

However, the war lords knew nothing of this in 1914 to 1918, and it was not until about 1926 that the lay public became aware of cosmic rays.

Robert A. Millikan and his associates at California Institute of Technology had taken up the subject in America, and Kolhörster with his coworkers had resumed the researches in Europe; and presently exciting stories began to appear in the press in report of the findings of these and other groups of investigators. Electroscopes had been sheathed in lead containers, and lowered into crevasses in the Swiss Alps under the overhanging ledges of glaciers. But the ice shield was no effective obstacle to a radiation that seemed all-pervasive. Other electroscopes were encased in waterproof boxes and lowered to the bottoms of glacial lakes on Californian mountaintops. But the hundreds of feet of water were not sufficient to absorb all the radiation from above, and the protected electroscopes gradually leaked their charges away, and at specific rates which correlated with one another. In other experiments, the detectors were carried into basement vaults, tunnels, and mines; but somehow the irresistible rays bored through soil and rock and concrete and steel, and had their usual way with the electroscopes.

It was out of such experiments that the first estimates of the energies of the rays were derived—from observations of their penetrating power.

2

But in 1932 a more exact method of measurement was attained by Carl D. Anderson, one of Millikan's associates in California, and with it came a memorable discovery.

Anderson made use of an English invention, a device known as the Wilson cloud chamber from its creator C. T. R. Wilson. In the moisture-laden air of the chamber microscopic droplets of water vapor are caused to cluster round invisible speeding electrified particles. The path of each moving mote is thereby rendered visible as a streak of cloud, and may be photographed. Anderson placed his cloud chamber between the poles of a powerful electromagnet, and in this magnetic field the particle was swerved one way if it carried a positive electric charge and another way if its charge was negative. In either case, the higher the energy of the particle, the swifter was its speed and the greater its ability to resist the pull of the magnet. Therefore, the degree of curvature described by the streak was a direct index to the energy.

When this powerful combination of apparatus was set in operation, Anderson found that particles were darting out of the metal frame of the cloud chamber at velocities greater than 100,000 miles a second. They were fragments of atoms blasted out of the metal by the accidental impact of cosmic rays.

The cloud tracks of these particles were so nearly straight lines that it was impossible to tell from which side of the chamber they originated. The powerful magnet was not strong enough to deflect them perceptibly, but Anderson hit on the maneuver of inserting a plate of lead in the center of the chamber. Thereafter the ejected particles had to pass through this barrier, and in doing so some of their energy was absorbed; consequently they emerged from the lead with lessened speed, and during the remainder of their journey the magnet was able to deflect them more noticeably. By these means Anderson could identify the direction of travel of the particle. He photographed cloud tracks whose curves indicated energies of thousands of millions of electron-volts, and measured for the first time the energy values of the activating rays.

On the afternoon of August 2, 1932, this apparatus produced a photograph that is now part of the history of science. Even while Anderson was in the photographic darkroom developing the negative, he recognized that he had made an extraordinary find. The image was that of a cloud track bent to the left under the measured force of the electromagnet—therefore he knew it must be the path of a positively charged particle, since only positives could move through the magnetic field in that direction. But this was a new kind of positive. Protons, the massive kernels of hydrogen atoms, are single charges of positive electricity and were the only simple units with this sign. But here in Anderson's photograph was a cloud track which said that it was made by a positive particle nearly 2000 times lighter than the proton. A bantamweight positive! Anderson and his coworker, Seth Neddermeyer, spent the whole of that night at the laboratory trying to figure the event out. It was for this discovery of the positron that Anderson was summonsed to Stockholm in 1936 to receive the Nobel Prize in Physics jointly with V. F. Hess. It was Hess, you remember, who was first to discover that the cosmic radiation increased in intensity the higher he arose in his balloon, and who proposed the idea that the strange penetration "enters our atmosphere from above." Anderson was the first to trap a cosmic ray in a cloud chamber and definitely measure its energy under the calibrated pull of magnetism, and first to distinguish among the cosmic-ray wreckage the peculiar wake of the positron. So the 1936 Nobel Prize in Physics was made a cosmic-ray award to be shared between these two discoverers.

After the initial spotting of positrons among the cosmic-ray smashings, various experimenters tried other radiations. It was shown that radium rays and other high-energy bombardments also may crash positrons out of matter, and today the physicists are invoking veritable showers of the new-found particles. But do not forget that it was by the

accidental blow of a cosmic ray that the great detection was made. In consequence we may claim a certain utility for the mysterious radiation. It has become a tool of science. While we cannot say that we have harnessed it, we have successfully used it to peep a little closer into the keyhole of the unknown.

3

Meanwhile, the nature of the cosmic radiation remains a tantalizing part of the unknown. At first it was believed that the rays were a form of radiant energy like x-rays, only of extremely shorter wave length and higher frequency of vibration. Such rays are electrically neutral, they travel in straight lines, and they are indifferent to the pull of the magnetic field. But a few years ago Kolhörster and his colleague Bothe, in Germany, found evidence that some cosmic rays behaved, not like light rays, but more like charged particles. And this raised a bold question mark.

It was pointed out that, if cosmic rays are charged particles, they should bend to the influence of magnetism; and if this be true, the Earth's magnetism should affect them and distort their paths of penetration into the atmosphere. Our planet is a whirling magnet, with one magnetic pole in northern Canada and the other in Antarctica, and the lines of magnetic force quivering out from these poles reach into space for many thousands of miles. Any charged particle headed earthward would be deflected by this vast planetary field of magnetism, just as the electrified particles smashed out of metals were swerved in the cloud chamber between the poles of Anderson's magnet. And so the cosmic-ray searchers began to look for a latitude effect.

First to find it was J. Clay, an Amsterdam physicist who was making an ocean survey for the Dutch government. Indeed, Clay discovered the effect some months before Kolhörster and Bothe published their question. As he traveled away from the equator, he noticed a slight differ-

ence in the intensity of the bombardment. Others confirmed this. A survey directed by A. H. Compton showed that these variations followed the Earth's magnetic latitude rather than the geographic latitude, an important distinction. Various types of cosmic-ray detectors were installed on steamships and by their automatic mechanisms were enabled to write a continuous record of the intensity of the bombardment as their voyages carried them across oceans, north and south to widely separated regions of the Earth. From these studies it has been possible to plot the zones of intensity on the map. All authorities agree that there is a latitude effect.

There is also a longitude effect, discovered independently by Clay and Millikan, and further investigation by other observers in many parts of the world has confirmed this. For example, Lima, Peru, and Singapore in the Malay Peninsula are both close to the magnetic equator, but are separated in longitude by half the circumference of the Earth, about 12,000 miles. The equatorial belt is a zone of low intensity for the rays, but apparently lowness in the Western Hemisphere does not mean the same as lowness in the Eastern. For the measurements show that the cosmic bombardment at Lima is 4 per cent more intense than that at Singapore. These variations are explained by the eccentric positions of the magnetic poles, for the North Magnetic Pole in the Boothia Peninsula of Canada is not exactly opposite the South Magnetic Pole in South Victoria Land of Antarctica. A line joining the two magnetic poles misses the Earth's center by about 300 miles. It is this lopsided shape of our terrestrial magnetic structure that makes the cosmic-ray intensity vary with longitude.

Still another kind of variation was discovered in 1933 by two scientists from the United States working independently in Mexico City. There was an idea that the particles might show some preferential direction in entering the Earth's atmosphere. Mexico City perched among its

mountains, high above sea level, is in the latitude of most rapid change of cosmic-ray intensity, and it was selected as a favorable site for the directional test. Luis Alvarez, then of the University of Chicago, and T. H. Johnson, of the Franklin Institute's Bartol Research Foundation in Philadelphia, were the researchers. Both men used the well-known scheme of mounting two or three cosmic-ray detectors in vertical series, one on top of the other in perpendicular arrangement. The wired connections were such that only when a ray passed through all two (or three) units would it make any record. Thus, by pointing the apparatus in different directions, it was possible to tell whether the intensity of the rays was greater from one point of the sky than another. Both men reported their discovery separately to their collaborator, M. S. Vallarta at the Massachusetts Institute of Technology. And the discovery was this: the bombardment from the west was fully 10 per cent more intense than that from the east. Later studies have detected this west-to-east effect in other latitudes and altitudes. In the United States it is about 2 per cent.

This preponderance of the bombardment from the west had been predicted on theoretical grounds, assuming that a certain percentage of the radiation was in the form of positively charged particles. Positive charges entering the Earth's atmosphere from outside should be swerved by our magnetic field in such a way as to appear to slant in from the west. Hence the discovery by Johnson and Alvarez added further evidence in support of the particle hypothesis, and also indicated that at least some of the particles were positively charged.

An obvious difficulty in all these researches is the sifting of the observed effects back to the primary causes, and determining from the secondaries which we detect the primaries which actuated them. For it is not cosmic rays that we record in our electroscopes, ionization chambers,

counters, and cloud tracks, but the fragments of atoms that have been smashed by an invisible something. Is that immediately causative something a cosmic ray, or some particle that earlier had been activated by a cosmic ray? This is the nub of the controversy over the nature of cosmic rays, the difficulty that our scientists find in identifying the primaries amid all the medley of mutilations that are continually occurring in our atmosphere, in our scientific instruments, perhaps in the bodies, the eyes, the brains of the observers themselves. It is pretty generally accepted by all authorities today that some of the cosmic radiation is in the form of high-speed charged particles, probably electrons and positrons. Millikan favors this view, but holds that the charged particles are only a minority group in the bombardment that actually gets down to sea level, the greater number of the missiles being in the form of a high-energy radiation. Compton takes a different view, regarding the bombardment as composed mainly of charged particles.

Both Millikan and Compton base their conclusions on experimental studies which represent perhaps the most far-ranging survey of a physical phenomenon that has ever been made within an equal period of time. Dr. Millikan uses a sensitive electroscope which includes an automatic recording device. All that is necessary is to keep the thing wound up, like a clock; then the automatic mechanism charges and recharges the electroscope at fixed intervals, and meanwhile photographs a record of the rate at which the apparatus discharges. Electroscopes of this type have been sent all over the world, carried high into the stratosphere by balloons, buried in mines and under water. Dr. Compton uses a sensitive ionization chamber, a device which measures the flow of currents of ions originated by cosmic rays, and it too has an automatic recording device which continually keeps tabs on any increase or decrease in the rate of ionization. This apparatus has been installed on

ships and carried on trips from Vancouver Island in Canada to Australia and between other widely separated places. It has made its record on mountaintops and from ascending balloons.

Early in 1937 scientists at the Department of Terrestrial Magnetism of the Carnegie Institution in Washington were experimenting with a new type of extremely light apparatus for measuring and reporting cosmic-ray intensities in the atmosphere. Previously, in the fall of 1936, Dr. Johnson at Philadelphia had sent up a balloon carrying a box equipped with a cosmic-ray detector wired to a radio transmitter. As the balloon rose from the ground to its ceiling 14 miles up, the automatic apparatus faithfully relayed by radio the signal of each cosmic-ray encounter. Even earlier, in experiments in India in 1934, J. M. Benade of the University of Punjab demonstrated a cosmic-ray meter transmitting its readings automatically by radio from balloon to ground. The new mechanism developed in Washington in 1937, by S. A. Korff, is extremely light—it weighs only 5 pounds—and it is cheap, so inexpensive, in fact, that no precautions are taken to recover the apparatus after it has completed its flight. The thing radios its report as it goes up, a receiver in the laboratory down on the ground picks up these signals and records them on a moving tape, and what becomes of the floating apparatus after it has completed its report is immaterial to the investigators. It may drift to sea or drop in a jungle without any serious loss. In former cosmic-ray surveys of the stratosphere the recovery of the apparatus with its contained record has been one of the chief anxieties, and in several instances coveted records have been lost with their fallen apparatus.

Doubtless many ingenuities must be resorted to before we unveil the complete story of the cosmic bombardment, and know to a certainty of what and how it is composed. There is no reason to expect the phenomenon to be one simple effect. Various factors may collaborate; the forces

that bombard us may be many, and not necessarily one. Similarly with the origin of the rays. Some may come from one source, some from another; some born of one process, some of another. The Universe is not simple—and "nature loves to hide."

4

Whatever the cause of the bombardment, there is no question of the tremendous energies carried by its missiles. These values can be rated rather reliably from the resulting wreckage. Several years ago Dr. Millikan undertook to reckon the density of cosmic radiation reaching the Earth. He found that it averages about 0.0032 erg per second for each square centimeter of our surface. Since an erg itself is a very small unit—the energy required to raise one pound to a height of one foot against gravity being 13,500,000 ergs—this fraction may seem to be a very small quantity. And yet, according to a recent computation by Dr. Korff, the whole energy of the Universe, the torrent of radiation thrown into space by the thousands of millions of stars of our Galaxy and by the stars of the millions of outside galaxies, totals a density of around 0.0069, only about double that of cosmic rays. So far as starlight is concerned, we are in a particular bright spot, surrounded as the Solar System is by the Milky Way; and because of our relative nearness to stars more of their radiation reaches us than reaches most places outside the galaxies. Indeed, most of the Universe is empty space, and Korff figures that Out There at a distance of a million light years from the nearest galaxy, the density of radiation from all the galaxies reaching that point would be only 0.000205. This is less than the thirty-fourth part of the energy density in our part of the stellar Universe. But cosmic rays are equally dense everywhere, so say our present hypotheses. From these considerations we are led to conclude that most of the energy flooding the vast wastes between the galaxies

is in the form of cosmic radiation, and that this is by a wide margin the preponderant energy of the Universe.

How strange! No theory predicted this, and no theory today can account satisfactorily for all its observed effects —yet experiment speaks unequivocally of the existence of the unpredicted unaccountable radiation. "This I know: it came to pass."

We are brought to a picture of reality in which most of the energy that activates the physical world is of a highly concentrated type, with millions of millenia ahead before it can reasonably be expected to degenerate to heat, or even to light.

The Universe, it would seem, is still very young. We are here, haply in this luminous neighborhood of space-time, in the childhood of the cosmos, and uncounted aeons await the adventuring pertinacity of restless questioning man. The fire snatcher need not fear a shortage of time, nor is there any threat of a shortage of problems to engage his time.

> Every hour the semen of centuries, and still of centuries.
> I must follow up these continual lessons of the air, water, earth,
> I perceive I have no time to lose.

Chapter VII · DEEPER INTO THE ATOM

Force, Force, everywhere Force; we ourselves a mysterious Force in the center of that. There is not a leaf rotting on the highway but has Force in it.

—THOMAS CARLYLE

WHEN the full story of our times is critically appraised, perhaps a century hence, many occurrences will assume an order of importance quite different from that assigned by our contemporary historians. Just as the obscure invention of gunpowder was an event more momentous than the widely heralded Battle of Waterloo, so there are little-known happenings of today that the sifting of the years will bring to the fore. They will become less obscure as time advances and their fundamental nature is more generally understood and their uses become manifest. For they mark permanent gains in man's ceaseless march and countermarch. Whatever the future of governments and individuals may be, the victories of the laboratories will stand as lasting assets of the race.

Among the recent victories is a discovery made in 1936 at Washington, D.C., at the high-voltage laboratory of the Carnegie Institution's Department of Research in Terrestrial Magnetism. It brought to knowledge an unknown force of the Universe, subjected the force to tests of meas-

urement and analysis, and defined the law by which the force operates.

For an approximate analogy, to suggest the significance of this American discovery, one must go back to the seventeenth century contribution of Isaac Newton—his discovery of the law of gravitation. As the Newtonian discovery brought a new and clarifying interpretation to certain mysterious behavior of planets that seemed to violate Galileo's rules of motion, so does this American discovery brilliantly illuminate certain perverse behavior of atoms that seemed to violate the established rules of electricity. The former discovery provided a force and a law that gave scientific meaning to celestial mechanics; the latter has provided a force and a law that give scientific meaning to atomic mechanics. Since it seems certain that in atomic mechanics are the sources and repositories of the world's energy, the consequences of this recent discovery appear to be of the highest promise to mankind.

If the world is built of atoms, as we believe, we must know atoms before we can expect to comprehend the physical reality. Nothing seems nearer, more conveniently at hand for investigation, than atoms. They are the air we breathe, the water we drink, the soil and rocks and trees and leaves; they are our physical bodies. And yet, perhaps nothing else is so hidden, so alien to our accustomed techniques, so beyond our reach. Instead of being the round hard solid particle that our fathers imagined, the atom is an abyss. Its depths are more remote in our scale of dimensions than the dim galaxies. The darkness beyond the faintest nebula is not more tantalizing to our limited organs of vision than is the blackness of the chasm within the atom.

In these atomic depths, energy breeds other energy. Here the strange eruptions of radium are initiated and controlled. There is a suspicion that here cosmic rays are born. The nature of substances, that which makes oxygen gregarious and helium a hermit, which gives iron sensitivity to

magnetism and caesium a responsiveness to light, which implants in the carbon atom such capacities as a "joiner" that the huge molecules of living substances are enabled to form and to hold together—all these and other distinguishing properties of elements, although apparently "external" attributes, are determined here in the innermost depths. In the atomic nucleus—and not in some far-off center of galactic rotation—is the power house of the Universe, multiplied endlessly, repeated in each of the innumerable hidden microcosmic systems. Are they the "mills of the gods"? the "looms of destiny"? the "mighty workings" that somehow spin our mortality? Physicists, as scientists, can not answer, though some in their more metaphysical moods may risk to pronounce on such questions. As scientists they believe that in the nucleus is the mechanism of matter stripped to its prime mover; hence the preoccupation of experimental physics today with this field. The nucleus is the battlefront for a score of brilliant strategists in America, Europe, and Asia. Against it the artillerylike discharge tubes, the mighty cyclotrons, and other atom-smashing devices are aimed. And it was along this front that the Washington experimenters won their 1936 victory.

The story of the discovery can be simply told. And I shall make the telling very simple, beginning with familiar concepts, recalling elementary features that are common knowledge, ignoring complications such as "wave behavior" and other items of quantum theory that are so important and indeed indispensable to the technician but not necessary to the present résumé, and shall focus attention only on features primary to our picture. Admit that we are imagists. All word pictures of atoms must necessarily be in the nature of parables, of moral tales, with the whites all white, and the blacks completely black. We understand among ourselves, of course, that white shades into black along gray no-man's lands; but these defy precise picturiza-

tion, and attempts to include all details in one parable result only in confusion. So let us be realistic and, therefore, imaginative. Our parable is frankly an approximation devised to illumine one facet of truth. If it does that it will have performed its intended function, and proved itself a useful parable.

I

A drop of water contains about 200 million million million molecules. No one has made an actual count, of course—there are not enough years in which to count that number of objects—but we know how much a drop of water weighs, we know how much a molecule of water weighs, and the rest is simple division. I mention the number to suggest the smallness of the scale of dimensions that we must accept in approaching the realm of the elementary particles. A drop of ordinary water weighs about 3600,000,000,000,000,000,000 atomic units. A molecule of water weighs about 18 units. The molecule is far beyond the limit of visibility even with the ultramicroscope, but we have chemical and physical ways of isolating it, measuring it, dealing with it quite objectively. Let us enter this molecular world.

Send a current of electricity through the water. The molecules begin to break up into three pieces each: one piece of oxygen and two pieces of hydrogen. These are the atoms. And by further manipulation with electricity we can break the atoms into yet more fundamental units—hydrogen into a certain number and arrangement of particles, oxygen into a different number and arrangement.

This hydrogen is highly interesting. Apparently it is the most abundant element in the Universe. Its atom is the simplest material system we know—an arrangement of two charged particles, one massive and electrically positive, the other lighter and more diffuse and electrically negative. The negative charge is the electron, and it revolves as a swiftly moving satellite round the positive charge, the proton.

And now we have reached the solid land we seek, the nucleus. For the proton is the hydrogen nucleus. If we could magnify the hydrogen atom so that its proton became just barely visible, the encircling path of the spinning electron would be about 6 feet from that center. Both particles barely large enough to be seen, and yet the revolving system outlines a sphere 12 feet in diameter? You can see why we think of the atom as an abyss, mostly empty space, its members relatively farther apart than the Earth is from the Sun.

The proton is the simplest nucleus now known. Apparently it is a single particle. Physicists find no difficulty in breaking hydrogen atoms, stripping off of each its revolving electron, and leaving the proton naked. Then they subject this unprotected proton to concentrated bombardments, using projectiles even more massive than the target, and shooting them at velocities of thousands of miles a second. But somehow the proton holds together. No one yet has been able to break one—at least, we have no clear evidence of such breakage. And so we assume that the proton is an indivisible unit. It is extremely massive. If you could lay a single proton in one pan of the scales of an infinitesimal balance, you would need to pile 1835 electrons in the opposite pan to bring the weight to equilibrium. Protons represent a tremendous amount of matter concentrated in small space. And the stuff of this matter appears to be electricity.

Apparently the proton is nothing but electricity—electricity of a peculiar behavior which we label positive. Similarly, the electron is pure electricity, but negative. A curious unexplained fact of nature is that the two particles exactly balance each other in electrical characteristics. That is to say, a piece of positive electricity, which is equal to 1835 pieces of negative electricity in quantity of *mass*, is equal to only 1 negative in quantity of *charge*. And so we find that despite its relatively enormous weight, the

proton is never attended by more than one electron. You may surround the atom with electrons, penetrate its depths with speeding electrons, but none of them will stick.

Sometimes we find a hydrogen atom of double weight. But the extra weight is entirely within the nucleus, for only a single revolving electron is found in these as in all other hydrogen atoms. Examine the double-weight nucleus and we see why this is so: it is a two-particle affair, made of one proton and one neutron. The proton is our familiar positively charged particle. But the neutron is a curiously neutral thing; for it has no charge, and, although its mass is about the same as that of the proton, it shows no electrical characteristics, neither attracts electrons nor repels them. More recently the atomic explorers have turned up hydrogens of triple weight; the nucleus here contains one proton and two neutrons, but even these swing only the single orbital electron. Apparently a nucleus, no matter how massive it is, can control only one electron with one proton.

With more protons, however, it can control more electrons. This we may demonstrate by examining that other partner in the water molecule, the atom of oxygen. Its nucleus is a complex of protons and neutrons. Some oxygens contain eight neutrons, a few contain nine, and a still smaller proportion of the world's oxygen contains ten neutrons; but every last one of them contains eight protons, *and only eight.* Also, every last one of the oxygen atoms swings eight orbital electrons, *and only eight.* This arrangement of matching one orbital electron against each nuclear proton appears to be one of nature's immutable principles of architecture; for as we go up the scale of atoms, the rule holds without an exception.

There is another rule of electrical behavior that we supposed held imperiously. This is the rule that if a body is positively charged and another body is negatively charged, they will mutually attract each other; but contrarily, two

bodies carrying the same kind of charge will be mutually repellent. Just before the upheaval of the French Revolution the Parisian scientist Charles Augustin Coulomb made very careful measurements of these electrical forces of attraction and repulsion, and discovered the law by which they operate. The nearer together the bodies are, the stronger are the forces; and the forces increase inversely with the square of the distance, just as gravitation does. This is Coulomb's law.

To illustrate its operation by a very obvious example, recall our enlarged model of the hydrogen atom with the proton just visible at the center and the electron revolving round it at a radius of 6 feet. Suppose we measure the electrostatic force of attraction between proton and electron at that distance. Then, if we bring the electron nearer, so that it is only half as far, or 3 feet, the force of attraction will not be two times; it will be the square of two, or four times as great. If we bring the electron still nearer, so that it is only a third of the original distance, the attraction will be magnified by the square of three, or nine times. It is easy to see from this why electrons in orbits closer to the nucleus move more rapidly. Just as the velocity of the Earth in its circuit generates centrifugal force to counterbalance the gravitational influence of the Sun, so does the velocity of the electron in its curving path engender such an effect to offset the attraction of the nucleus. Hydrogen atoms would collapse were it not that the electron moves so swiftly. A velocity of 1350 miles a second has been calculated for the innermost orbit of ordinary hydrogen.

These mutual relations between the positively charged nucleus and the negatively charged satellite appear to conform strictly to Coulomb's law. This is true not only for the simple hydrogen atom; it has been observed also in the behavior of more complicated atoms. The eight electrons of the oxygen atom, for example, move in their orbits at

velocities proportional to their distances from the eight protons in the oxygen nucleus.

Eight protons in a nucleus? The reader who has followed the parable thus far may reasonably object. How can the oxygen nucleus hold together?

This indeed is our dilemma. The nucleus of oxygen is very small, not much larger than the nucleus of hydrogen. But the primary objection is not that so many particles should exist in a space not much larger than one of them, but that the particles of positive electricity should stay together at all.

Coulomb's law insists that positive particles repel one another in the same degree that they attract negative particles. Abundant experience confirms the law. There are electric motors activated by this force of repulsion; it operates in telephone and telegraph circuits; it is used in other industrial applications. No behavior of electricity is better known among the large-scale phenomena of electrical engineering. Engineers only occasionally deal with pure charges of electricity; most of their work is with gross bodies carrying charges. But the chemist Frederick Soddy, after measuring the force of repulsion that exists between two free protons, made an interesting calculation.

A gram is a small quantity in our everyday world; it rates about the twenty-eighth part of an ounce. But Dr. Soddy's figures show that if it were possible to accumulate a gram of protons at one pole on the Earth's surface and another gram at the opposite pole on the other side of our globe, the mutually repellent force of these two small quantities of positive electricity would be equivalent to the pressure of 26 tons, even at that distance of about 8000 miles. Try to imagine, then, what should be the repulsion of proton against proton within the narrow zone of the atomic nucleus, where dimensions are reckoned in tenths of million millionths of an inch.

On the logic of Coulomb's law one could expect to find no atoms in the Universe except those of hydrogen, since

it should be impossible for more than one proton to occupy a nucleus. And if by chance two or more high-speed protons collide and find themselves accidentally associated in close quarters, Coulomb's law required that they instantly fly apart at terrific speeds of repulsion. Instead of this, the searchers found that the physical world includes a complete sequence of "impossible" structures—the helium atom with 2 protons in its nucleus, the lithium with 3, beryllium with 4, boron with 5, carbon with 6, and so on up the scale to the heaviest, uranium, with its gigantic family of 92 protons housed with 146 neutrons in the diminutive confines of nuclear space.

This uranium atom, to be sure, is a wobbly structure. Every now and then one ejects a cluster of protons and neutrons from its center, to leave a less crowded residue. This residue we call radium, and its nucleus in turn also explodes with a series of ejections, breaking down to form the simpler polonium. Finally polonium, after ridding itself of a cluster of 2 protons and 2 neutrons, settles into the stable structure we call lead. But why should lead be stable? Its nucleus, even after the successive explosions, still contains 82 protons, and each of them should waste no time in getting away from the hated presence of its fellows.

Such is the anomaly that for more than 20 years defied explanation.[1] Coulomb's law, which ruled precisely in the atomic environs and within the spaces between nucleus and orbits, did not apply to bodies in the central core. Why

[1] Until the discovery of the neutron (1932) atomic nuclei were thought to contain protons and a smaller number of electrons, but the nature and binding forces of such a structure were a complete puzzle, outside all conception of theory. The neutron helped the situation but little, although it conceivably could act as the intermediary for binding protons together in spite of their repulsive forces. In fact, a whole theory of nuclear structure, now abandoned, was built up on this hypothesis as soon as specific forces, assumed to be attractive, were demonstrated by neutron-scattering experiments to exist between neutrons and protons. These forces, it is now known, assist the proton-proton and neutron-neutron forces in binding the nuclear particles together.

was it flouted there? By what supreme court, by what more powerful ordinance, was it overruled?

The Washington experiments of 1936 brought the first satisfactory answer to that question. They penetrated the inner fortress to demonstrate directly the existence of a mighty force which is operative only within the small dimensions of the nuclear zone—a force more powerful than the Coulomb force of repulsion, more attractive than the Newtonian force of gravitation: a sort of central traffic control which dominates and directs the other material forces. Apparently it is responsible for the wide variety of atomic forms that matter may assume. Also we are to think of it as a unifying agency which underlies all physical reality. Without it there could be no metal, no carbon, no living cell, no Earth, no Sun, no Galaxy, no manifold Universe—there could be nothing more complex than hydrogen, and the Whole would be only a vast cloud of diffuse hydrogen gas interspersed or combined with free neutrons. At least, such is the picture we infer from the facts we know. Our new-found force is the medium that holds the world together. It is the invisible tie that binds.

2

Many of the great discoveries of science were accidental finds, but this binding force of the nucleus was not chanced upon by accident. Its detection is the culmination of 10 years of experiments aimed directly at this mystery.

When the Carnegie Institution of Washington established a Department of Research in Terrestrial Magnetism in 1904, the specialists in charge realized that their studies must lead eventually to atomic physics. At that time no one dreamed of massive central nuclei surrounded by revolving electrons. But no one doubted that the secret of the Earth's magnetism, of whose reality the quivering compass needle is perpetual witness, must be sought not only in the Earth and its atmosphere but also in the in-

visible molecules and atoms of the needle itself. Matter must be minutely explored for the magnetic mechanism within it. The early studies were directed at large-scale phenomena, magnetic surveys of the continents and seas, and mapping; but in 1926 a definite program of subatomic research was initiated. By this time considerable data on the intimate behavior of subatomic parts had been accumulated by laboratories in Europe, Canada, and the United States. Conspicuous among the anomalies thus brought to view was this curious inexplicable behavior of protons within the nucleus. The Coulomb forces are so fundamental to our idea of the response of the compass needle that any variation or suspension of their action in any region of the Universe must be a cause of concern to explorers of magnetism. And so, among the problems outlined for investigation by the department was that of the nature of the nuclear mechanism. A special laboratory was built to house the research. Special apparatus was designed and installed: first a high-voltage discharge tube capable of delivering momentary blows with a pressure of about 1,000,000 volts; then an electrostatic machine and tube continuously energized by 500,000 volts; and finally the present towering atom smasher of 1,200,000 volts capacity, with which the great detection was achieved.

The detectives in this search were led by Merle A. Tuve, and the group included L. R. Hafstad, O. Dahl, and N. P. Heydenburg, physicists all. At various times during the 10 years other men were on the staff, and each contributed some spark of illumination to the slow plugging through the darkness. But I am naming above the fortunate four who were working with the big atom gun that cold January day early in 1936 when the first rumors of the new result began to trickle in. Months were to pass before the discoverers made any public announcement of what they had done—for an effect so apparently exaggerated must be tested, checked and rechecked, and submitted to the

penetrating eye of mathematical analysis before it could be announced as a certainty. Indeed, nearly as important as the observations themselves, which by direct inspection only showed the failure of the Coulomb law, was this mathematical analysis of the observations in terms of the "wave mechanics," a service performed by Gregory Breit and two associates. All these tests and calculations, the checkings and recheckings, were concluded successfully, and the full story of the discovery was reported to the international group of scientists assembled at Cambridge in September of 1936 for the Harvard Tercentenary Conference.

The thing sought in the experiments was a definite measurement. We may outline the logic of the campaign in three steps. Observation had shown (1) that protons dwell together within a nucleus, and (2) that protons outside a nucleus are repelled; therefore, reasoned Tuve and Breit and their associates, there must be (3) a critical distance at which the force of repulsion is overcome and within which the protons become reconciled to one another's presence. To find that critical distance became the first objective.

The means used were those of bombardment. Suppose you have a vessel full of pure hydrogen gas of a measured density. And suppose you fire a stream of protons into this atmosphere of hydrogen. Each hydrogen atom, remember, has a proton in its core; so what you are doing is a bombardment of protons with protons. Some of the bombarding protons will approach the nuclear protons head on, others may pass close by on either side, and in every case the mutual forces of repulsion will act to rebuff the particles. They will never touch; the collisions will be only approaches and the nearer the approach the more powerful will be the repulsion. Since targets and projectiles are of equal mass, the effect will be a scattering. But the scattering will not be heterogeneous; it will be quite systematic in its directions. Just as it is possible to predict the behavior of

billiard balls from the angle at which the projectile ball strikes the target ball, so it is possible to predict the behavior of the protons. Some years ago the British physicist N. F. Mott made a careful mathematical study of this phenomenon, and predicted the relative number of protons that would be scattered from each angle of approach in obedience to Coulomb's law.

All these data of the ratios and numbers of particles that would be turned back at each angle were available for Dr. Tuve and his laboratory crew. They provided a sort of bench mark, a measurement of the norm of behavior to be expected of protons acting according to Coulomb's law of repulsion. Any departures from this norm might be regarded as evidence of the breakdown of the law. And what the Washington experimenters proposed was to bombard hydrogen gas with faster and still faster protons until they got a scattering different from that predicted by Mott's calculations. The greater the velocity of the protons, the greater would be their momentum, and therefore the greater would be their ability to overcome the repulsion and approach closer to the nucleus.

This game of aerial billiards with ultrascopic particles seems very simple in principle, but it proved almost infinitely difficult in execution. The measurement of the angles could mean nothing specific unless there were an equally accurate measurement of the purity of the particles, of the density of the particles in the hydrogen at the target end of the apparatus, and of the velocity of the stream of projectiles. Very precise control was required in each of these items. Without going into details of the successive steps, I can say that many expedients, many variations, many skills were tried before the actual scattering experiment was even attempted, and before the present apparatus with its marvelously exact control was attained.

The atomic artillery piece looks its part—a sort of super machine gun mounted on its sprawling tripod, towering 20

feet above the floor, with its muzzle pointing straight down and passing through the floor into the basement room below. At its top is an aluminum sphere of 6 feet diameter, the loading device. Descending from the sphere is a vacuum tube of sturdy glass, the aforesaid muzzle. Charges of positive electricity from a generator are fed by a traveling belt to the aluminum sphere, and these are allowed to accumulate on the metal surface to build up a pressure as high as 1,200,000 volts, under conditions of accurate control and precise measurement. This pressure discharges steadily through the long vacuum tube; and by releasing protons into the tube at the top, the gunner provides projectiles for the voltage to work on. The protons may be speeded to any desired velocity, depending on the voltage applied; and, what is equally important, the installation includes clever focusing devices to concentrate the stream, and an analyzing magnet at the bottom to pull out stray particles, unwanted molecules, and stragglers along the fringes of the stream. Thus the instrument is able to deliver to the target chamber at the bottom of the tube a finely focused stream of homogeneous protons all moving in parallel lines and at the same velocity.

In effect, it is as though you had generated a continuous lightning bolt, had harnessed it within the confines of the vacuum, had sifted out all heterogeneous and diffuse elements, and concentrated its missiles into a steady beam narrowed for a measured attack on anything you choose to place as a target in its path.

The target chamber in which the scattering takes place is in the basement room, at the focus of the tube. This chamber is a small cylindrical compartment about 6 inches in diameter, into which highly purified hydrogen gas is released. And built into the compartment is an ion detector mounted on an axis so that it may be pointed toward the incoming stream of projectiles at any angle, ranging from zero to ninety degrees. Here is the final link in the chain of

stratagems. For, by knowing precisely the original number of particles in the beam, and the number of particles (hydrogen gas) in the chamber, and then by counting the actual number of rebounding or swerving particles which smash into this detector at each of its angular positions, you can tell whether or not the projectiles are being scattered according to Mott's calculations—*i.e.*, according to Coulomb's law.

When the thing is operating there is an awesome hum, the drone of the generating mechanism. Occasionally, when affairs are not well adjusted, a spark will flash with a lively crackling from the charged belt to the ceiling above the sphere. And to stand on the floor of this room is to place oneself in the presence of invisible influences which curve through space along the mysterious lines of force which radiate from charged bodies. Indeed, one becomes a charged body. My finger put out toward another person sprayed sparks.

But the workers spend most of their time in the basement room where the targets are manipulated. Lead salts fused in the glass of the tube protects them from random x-rays and other stray radiations that might be generated by chance collisions of the protron stream passing down the tube. Very accurate is the detector device which measures the number of protons scattered at each angle. Each of the bounced protons gives a signal, the signal is amplified by a powerful device, and thereby these infinitely small movements of infinitely small objects are brought within the range of man's perception.

Tuve and his associates began the bombardment with a stream energized by a pressure of 600,000 volts, which means that the protons had velocities of 6720 miles a second. The detector registered the scattering for each angle, and found that Mott's calculations held, that Coulomb's law of repulsion was operating quite normally. Then the bombarders increased their artillery fire; the

pressure was increased to 700,000 volts, speeding the particles to 7200 miles a second—and Coulomb's law still held. They quickened the attack to 800,000 volts, producing velocities of 7700 miles a second—and the ancient law began to show evidence of failure. Then the electrical potential was raised on up to 900,000 volts, the stream of protons moved with the momentum imparted by velocities of 8200 miles a second, and now—something new began to happen!

Instead of recoiling or swerving as before, the projectiles moved in toward their nuclear targets. The change in the number of scatterings from certain significant angles said so, and spoke unmistakably. The inertia of the fast-moving protons carried them headlong through the zone of rapidly increasing force of repulsion until at last the critical distance had been attained by sheer brute momentum, the long steeply ascending barrier of the nucleus had been mounted, and the invading proton was admitted to the citadel.

Hundreds of experiments of this kind were performed. There could be no doubt that the Coulomb law had failed—but why?

The records of all the observations were forwarded to Gregory Breit for further analysis. Dr. Breit is a mathematical physicist, was long on the staff of the Department of Research in Terrestrial Magnetism—indeed he was the leader of this atom-smashing crew at the beginning of the campaign back in 1926—and is still connected with the Washington laboratory as a research associate. But he is now professor at the University of Wisconsin, and in the winter of 1936, when this body of observational data reached him, chanced to be in Princeton attending the Institute for Advanced Study. Right in the neighborhood, across the corridor in Palmer Physical Laboratory, was Edward U. Condon, whose mathematical explorations of atomic behavior have given him wide experience with these technicalities. Dr. Breit called Dr. Condon into consultation, and together they began to dissect the batch of

plotted curves and numerical tabulations. Certain details of the problem made it expedient to consult another expert, and R. D. Present of Purdue University made the third member of this mathematical team. By applying the highly complex calculations of "wave mechanics" to the experimental observations, Breit and his associates showed that beyond all doubt the observed failure was not attributable to a possible added repulsion (for a sudden sharp increase here might also distort the predicted scattering), but was actually a result of encountering for the first time the long-suspected *attractive* force which binds particle to particle within the nucleus.

The outcome of the mathematical analysis of these experiments may be conveniently summarized as four findings.

1. The critical distance at which the Coulomb force of repulsion between protons breaks down is about 1/12,000,000,000,000 of an inch.

2. The sudden change which occurs in the relations between two protons separated by this critical distance can be explained if we assume the existence of a superior force of attraction which at that and lesser distances dominates the two particles.

3. The binding power of this force, as it operates between two protons at the critical distance, is approximately 10^{36} times greater than the Newtonian force of gravitation between the two protons.

4. Not only protons but also neutrons are subject to this powerful force. The attractive force between a proton and a neutron or between two neutrons is the same as that between two protons, except for the absence of the Coulomb repulsion when the chargeless neutrons are involved. These conclusions regarding neutrons are derived indirectly from other data, but the evidence seems to indicate that the nuclear force of attraction is somehow intimately associated with the mass of these primary particles, and depends little, if at all, on whether or not they are electrically charged.

To grasp some concrete idea of the enormity of this force we must resort to a comparison. Remember that the proton is inconceivably small. Its weight is less than this almost infinitesimal fraction of a gram:

$$\frac{1}{600,000,000,000,000,000,000,000}$$

And a gram is $1/454$ of a pound.

Now the measurements show that the pull of proton for proton within the region of the nucleus is so great that the two tiny particles move toward one another as though impelled by a pressure of from 10 to 50 pounds. If the Newtonian force of gravitation operated on the same scale, a feather on the Earth's surface would weigh billions of tons.

When free protons or neutrons are captured and incorporated into a nucleus, a certain proportion of the original mass of the particles is converted into energy. The nuclear force, by its bringing of the particles together, seems to take a toll out of their substance, and the whole nucleus becomes lighter than the sum of its separate parts. Thus, if we weigh a single proton the scales show a mass of 1.0081; if we weigh a single neutron, 1.0091. The total weight of the two particles therefore is 2.0172. But when they unite to form the nucleus of a heavy hydrogen atom, the mass of the resulting nucleus is only 2.0147 in weight. The difference, .0025, represents the energy of the binding force which holds the two particles together. By computation we find that .0025 of mass is equivalent to 2,200,000 volts of energy. And experiment shows that to crack a heavy hydrogen nucleus and separate its neutron from its proton requires the blow of a projectile moving with an energy exceeding 2,200,000 volts.

3

By these means, and in other ways as well, the newfound phenomena check. There dwells within the centers of

atoms—atoms of the rocks, atoms of the air, atoms of flesh and blood—this titan of forces, this indefinable dryad, if you will, which pulls masses together, expends tremendous energy to bind them into nuclear systems, and in the process makes the masses less massive.

Various names have been proposed for the new entity. One suggestion is that it be called the force of "levity," since the effect is to reduce the masses of the bound particles and therefore to make them lighter; but surely levity is not the most fundamental aspect of this tie that binds. Another suggestion is "supergravitation"; but the newfound force is so superlatively super that this title sounds makeshift. The thing has also been referred to as the force of "nucleation," suggesting its effect in causing elementary particles to consolidate their influences, to nucleate into atomic cores. Since the force manifests itself as the central force of all physical nature, it deserves an unequivocal name.

We may surmise that gravitation, magnetism, and the electrical properties of attraction and repulsion are only special cases, or conditioned reflections, reactions, or interactions, of this mighty central Something that holds the world together.

And what shall we say of atomic power—that dream of the modern alchemists who have said that energy sufficient to propel an ocean liner across the Atlantic is locked within a teaspoon of water? Surely its secret lies here. Reckon the billions of billions of protons and neutrons contained in water, remember that each is bound to its neighbor with a force of millions of electron-volts, that proton is linked to proton as if with a pressure of many pounds, and sum up the total. If it were possible to treat a teaspoon of water expeditiously, to cause the protons of its hydrogen atoms to combine into more complex nuclear patterns and thus form atoms of heavier elements, the energy released in binding these interior particles together would total several

hundred thousand kilowatt-hours—quite sufficient, if harnessed, to drive a steamship from New York to Havre. But we must admit that we know no means of harnessing the forces even if we were able to release them economically; and the plain fact is that our present methods of separating and synthesizing nuclear structures require more energy in the bombardment than we get back from the transmutations. The utilization of atomic energy is a goal for the future—as far as we can see today, for the very distant future—but a beginning has been made in the Washington experiments. The discovery and measurements of the forces provide a firmer basis for our dreamers and, let us hope, for our future engineers.

Dr. Tuve and his associates are planning deeper forays. In 1937 they began the construction of a new electrostatic generator and discharge tube designed to operate at potentials above 5 million volts. Protons accelerated by this electrical pressure will hit the target with a velocity of 19,300 miles a second. The resulting momentum should carry the projectiles into the nuclear zones of massive atoms, such as those of the metals, whose inner cores present complexities in striking contrast with the simplicity of hydrogen. The problem is a peculiarly enticing one, and various laboratories in Europe and America are now engaged in a strong attack upon it. The frontiers have been crossed, but a vast hiddenness still awaits exploration. The nature of the internal structure, how the interior particles move and interact within their narrowly bounded zone, their degrees of freedom and compulsion—such questions beg for answers. There are inklings of news from within, fragmentary flashes of this and that, and theorists are never idle with their charming mathematical symbolism. But the ultimate battle must be won by the experimentalist. Theory must be tested and proved by experience, before we can go in and possess the new land.

Chapter VIII · THE NEW SCIENCE OF SOUND

Hear ye not the hum
Of mighty workings?

—JOHN KEATS, SONNET XIV

It is not only in the microcosmic realm of atomic transmutations and mysterious nuclear forces that the world of physics has become new again, and exciting. Even so ancient and familiar a technology as acoustics, which dates from the time of Pythagoras, has inhaled new life and received new illumination from the recent applications of electronics. Indeed, our modern engineering of sound waves is a thing of the telephone era. And in the last decade, with the swift rise of the radio and the talkies and their insistent demands upon the laboratories, so much that is new has been discovered and so much that was old has been rescued from guesswork that acoustics today may be rated among the youngest of the sciences. Recent experimental findings overturn many of the classical formulae. Physicists are beginning to use sound waves as probes for inquiring into the intimate behavior of gaseous matter. Chemists are learning that there is a chemistry of sound. Engineers are putting the more precise knowledge to work in new musical instruments, in new arrangements for enhancing the auditory characteristics of rooms, and in clever schemes for reducing the noise nuisance.

Many devices enter into the equipment of the new acoustics, but two may be regarded as the lever and fulcrum of our advance: the microphone, and the thermionic vacuum tube.

The microphone is the electric ear which picks up waves of sound and converts them into a faithful counterpart of waves of electricity. By transforming sound patterns into electrical patterns we reduce them to more manageable phenomena, and on this facility hinges the whole rapid development.

The vacuum tube is so versatile that a full list of its services would be a lengthy catalogue. In general one may say that the vacuum tube makes possible the amplifier which is indispensable in long-distance telephony, in radio transmission and reception, in the acoustical performance of sound pictures, and in many other applications.

Both microphone and vacuum tube are essential parts of the new instruments of measurement—the sound meters, frequency analyzers, and other mechanisms for the exact determination of the characteristics of vibration. It is these sensitive gauges that have given a new precision and an unaccustomed control to acoustics. They have substituted for the judgment of the ear, with its variable sensitivity and its liability to psychological bias, the impersonal verdict of the pointer reading. Even in those fields in which human judgment must be the final arbiter the electrical measuring devices have enabled us to make more accurate tests of what the ear hears. They have revealed much that was unknown and corrected much that was wrongly believed.

I

It has long been believed, for example, that each of the three recognizable characteristics of a musical tone is determined by a single physical characteristic of the sound wave. Pick up any standard textbook of physics and you

will doubtless find some such pronouncement as this: The *pitch* of a sound depends upon the frequency of its vibration, the *loudness* on the amplitude of its wave, and the *timbre* on the shape of its wave. This generalization reduces the subject to a neat formula, pigeonholing each characteristic with a single determining cause—but recent research shows that it does not tell the whole story.

Experiments conducted by Harvey Fletcher and his associates at the Bell Telephone Laboratories demonstrate that a variation in any one of the three factors *may* affect each of the tonal characteristics. They prove that pitch may be changed by altering the amplitude or the wave form as well as by altering the frequency; and similarly that loudness and timbre may respond to changes in frequency or amplitude or wave form.

In the case of pitch, for example, tones that have frequencies of about 200 cycles (or vibrations a second) appear to be very sensitive to changes in loudness. This is the pitch that approximates that of middle *A* on the piano, and is well within the range of most human voices. Dr. Fletcher has found that if a tone of 200 cycles at a certain loudness is amplified a hundredfold, its pitch may be heard as a semitone lower. With still increased loudness the lowering of pitch is yet more pronounced. Thus as the sound is intensified in volume its pitch tends to shift from the soprano toward the bass end of the scale.

The relation of loudness to changes of pitch is also experimentally proved. For example, Fletcher finds that if a tone of 100-cycles frequency is sounded with an intensity corresponding to 35 decibels above its threshold of audibility, the tone gives a sensation of loudness equal to that of a 1000-cycle tone at 60 decibels. Thus, as a low-pitched tone is raised above its threshold intensity it increases in loudness much faster than does a high-pitched tone. It covers as long a range of loudness in going up 35 decibels as the high-pitched tone does in rising 60 decibels.

In the shaping of timbre—and by timbre is meant the quality which enables the ear to recognize one sound of a given pitch as violin music and another sound of the same pitch as vocal or piano music—equally complicated factors enter. This may be demonstrated when violin music is reproduced over a high-quality electrical system which permits the sounds to be amplified to any degree of loudness. By the use of electrical filters or other analyzing devices it is possible to show that, no matter what amplification is used, the wave form remains the same, with all its overtone structures preserved intact—and we used to think that these structures alone determined the timbre. But if the violin vibrations thus unaltered in wave form are amplified to a loudness 10 to 100 times that of the sound coming directly from the violin, they lose their violin quality and are no longer recognizable. Other experiments show that the timbre may be changed by varying the pitch.

All these discoveries have come to a focus since 1930. And while the research cannot by any means be said to be complete, the results are sufficiently representative to give composers, singers, orchestra directors, and others an obvious hint. Glorious as is its past, music may have a still more distinguished future when these new relations of its physical components are made use of by its creative artists—when acoustical art builds its beauty anew on the realities of acoustical science.

2

The sounds we hear are only a fraction of the sounds that exist. Indeed, it seems likely that the silent waves are more numerous than the audible pulsations which make up our speech, our music, and our noise.

Some sounds are inaudible because their vibrations are of a frequency beyond the ability of the nervous system to register. They are comparable to the ultra-violet light, whose waves oscillate with a rapidity so great that the eye is in-

sensitive to their vibrations. It is only by means of instruments that we are able to detect these invisible radiations, and similarly it is only by ingenious devices of apparatus that we are able to prove the presence of silent sounds. Of course their existence has long been suspected. We hear a hummingbird sing; his notes soar higher and higher until finally nothing is heard. And yet his mouth is open, his throat is pulsing, there is visual evidence that he is still singing. Certain crickets also shrill their calls at a very high pitch.

Recently, at the Research Laboratory of Physics at Harvard, George W. Pierce and his associates set a trap to catch these unheard melodies. They made use of certain characteristics of crystals by which it has been found possible to control the vibrations of electrical devices. Crystals cut of Rochelle salt, for example, have a wide range of response and will vibrate in phase with sound waves that strike them.

Dr. Pierce and his coworkers installed a Rochelle crystal in a parabolic horn, and made this the receiving end of a very sensitive sound detector. The apparatus is so responsive that it can pick up the sound of a cricket at a distance of 900 feet. When the sound waves gathered by the horn strike the crystal, the crystal responds at their frequency and by its vibrations gives rise to a varying voltage. The sound waves of the cricket's notes are thereby converted into electrical vibrations, and these weak electrical waves are amplified with the aid of vacuum tubes and other apparatus. The result is a pattern of electrical vibrations corresponding precisely in frequency to the pattern of sound waves. But how to detect that inaudible frequency? Dr. Pierce reasoned that if he combined with the unknown vibration another vibration of a known frequency—that from an electric oscillator, for example—and applied the two superimposed vibrations to a vacuum-tube detector, certain coincidences of the two sets of waves should occur.

And these coincidences or beats should make an audible vibration in the loud-speaker. By analyzing the frequency of this audible vibration, and knowing the frequency of the super-imposed vibration from the electric oscillator, one should be able to determine the frequency of the original sound which actuated the Rochelle crystal.

The plan worked. A small brown field cricket (*Nemobius asciatus*, by name) is shown by this apparatus to give off a variety of high-frequency sounds. The main pitch of his song was recorded as about 8000 vibrations a second, with other notes strongly registered as 16,000, 24,000, and 32,000 cycles. Nor is this the limit. In their laboratory the Harvard scientists have produced and detected sounds having frequencies up to 2,000,000 cycles, and have demonstrated the existence in nature of sounds as high-pitched as 40,000 cycles.

This is far beyond the range of human hearing. Few ears can discern sounds of frequencies above 20,000 cycles, and for most adult ears the limit is nearer 18,000. The higher the frequency of a sound, the shorter is its wave length; and there can no longer be any doubt that waves of exceedingly short length and very high frequency are continually agitating the air. Not only the crickets and other insects, but scores of frictional encounters in nature, the rubbing together of the hands, the blaze of an igniting match, the vibration of leaves stirred by the wind, the friction of clothing, are shown by these experiments to produce, in addition to audible noises, many sounds of pitch too high for human hearing. In the ticking of a watch certain sounds of 30,000 cycles were detected at a distance of 30 feet.

In addition to this unheard symphony of supersonics which surrounds us there is a medley of audible noises perpetually present but rarely if ever recognized because of the competition of more energetic air vibrations. For example, the beating of the heart makes a sound, and some

of this sound would be heard if our hearing were not already monopolized by the continual agitation of louder sounds. These latter have a masking effect—like that of a passing trolley's clanging when the listener is trying to give ear to a delicate piano melody. When the masking noises are shielded off, the weaker audibilities become perceptible. In a perfectly soundproof room (an acoustical utopia that does not exist) the listener would be able to hear the minute sounds made by his own pulse, the flow of blood through arteries and veins, the pumping of the lungs, the inflow and outflow of breathing—faint audible sounds which actually have been measured.

To measure sounds of low intensity it is necessary to isolate them. An example of how this may be done was demonstrated in a New York University classroom. E. E. Free and his associate C. A. Johnson fitted up a cup with a sensitive microphone as its bottom, connected this electric ear with a powerful amplifying system, and closed the circuit through a loud-speaker. When the cup was filled with a handful of wheat grains, violent noises issued from the loudspeaker—crunchings and grindings so raucous that professors in classrooms down the hall found it necessary to protest against the disturbance. What was it? Dr. Free searched through the wheat and found here and there a grain with a tiny puncture. When these defective grains were cut open each was found to contain a worm, the larva of a weevil. It was the twistings and munchings of these creatures within the granules of wheat that made the noise. The microphone picked up the weak sound waves and isolated them as waves of electricity, the amplifying system magnified the waves to the appointed level of intensity, and the loud-speaker converted back into sound these magnified vibrations.

The apparatus operated as a sound microscope. The main problem in its design was the amplifying system. For the amplifier must be powerful enough to give audibility to the

vibrations generated by the insects without unduly magnifying the noise of the electrons flowing at thousands of miles a second through the vacuum tubes of the delicate apparatus itself. Calculation shows that these electronic sounds measure only a little below zero on the decibel scale of loudness, and experiment demonstrates that with amplifications running into the billions, these electronic vibrations become audible. So, to avoid imposing the zoom of the atomic particles upon the noise of the squirming insects, Free and Johnson designed their amplifier to operate at a mere ten million million fold magnification. That was sufficient, however, to make it possible for the turning of a worm to outshout a professor. If an ordinary whisper were magnified by the same factor and released to the air in New York, I am told that it should be heard in San Francisco—a blast of sound equivalent to that of the explosion of a major volcano.

The amplified whisper would take on such huge proportions because it begins so much higher up the scale of loudness. A whisper measures about 25 decibels, whereas the insect noise may be zero or below. The decibel gets its name from an earlier unit chosen some years ago by telephone engineers to measure the rate of fading of telephone signals sent over a wire. They called their unit the bel, after Alexander Graham Bell, and defined 1 bel as an intensity 10 times that of the zero level, 2 bels as 100 times that of zero, 3 bels 1000 times, and so on—each added bel multiplying the magnitude by 10. Even before this scale was adapted by acousticians to the measurement of sound intensity, it appeared that the bel was too large a unit. So each bel was divided into tenths, decibels. In general we may say that a decibel represents about the smallest difference that an average ear can distinguish. In the laboratory the unit is defined in million millionths of a watt; but perhaps its meaning may be suggested more graphically by mentioning the decibel equivalence of a few familiar sounds.

The noise of ordinary breathing measured at a distance of 1 foot registers about 10 decibels. It is one full bel; therefore is 10 times louder than a noise of zero magnitude on the scale.

The rustle of leaves in a breeze rates about 20 decibels—2 bels, 10 times louder than the level of breathing, or 100 times the zero level.

The noise made by turning the pages of a newspaper approximates 30 decibels. The average intensity of conversation is 65 decibels. That of piano practice is 75. Five units higher up than that of the piano thumping, at 80 decibels, is the noise of a passing motor truck. A lion's roar has been metered at 95 decibels—and this is also the loudness of the river falling on the rocks below Niagara, and that of a passing elevated train in New York. The clatter of a steel riveter mounts to 105 decibels. Beyond this the nerve response becomes pathological, and at somewhere near 130 decibels—ten million million times the zero point of intensity—sound is painful in the literal sense.

In using the term zero point it is not to be understood that the sound at that level is of no value. Zero decibels is the reference level on our scale of loudness, just as zero degrees is the reference level on the centigrade scale of temperature. In general zero is thought of as approximately the threshold of hearing, but this is true only for vibrations of certain frequencies. For those of other frequencies the threshold may extend below the zero mark; while for an even wider range, both at the bass and at the treble end of the sound spectrum, the threshold of hearing is above zero.

Similarly, the threshold of painful sounds must be charted as a curved line. While it is near or beyond 130 decibels for a limited number of low frequencies and a limited number of high frequencies, it does not rise even to 120 decibels for certain sounds intermediate between these extremes.

The thermometer again provides a simple analogue. Just as the freezing point of water is at one temperature and that

of mercury at quite a different temperature, so is the threshold of hearing for a deep bass note quite different from that of a piccolo's high treble. A high C on the piccolo, vibrating 4096 cycles a second, may be caught by some ears when its loudness is a few decibels below zero, whereas a low C on the organ, vibrating 32 cycles, must be sounded with an intensity of at least 60 decibels to be heard at all. The threshold of hearing for this organ tone thus requires an intensity level more than a million times louder than that of the piccolo tone.

A similar relativity between pitch and loudness exists at the other extreme. The threshold of painful sound, the boiling point on our noise thermometer, is close to 130 decibels for the low C of the organ; but for the high C of the piccolo it may begin to be felt at about 118 decibels. Quicksilver can stand more heat than water can before it boils, and so is the ear able to endure a louder bass sound than it can a sound of high soprano.

3

When the sound meters, filters, analyzers, and other devices have done their jobs—have isolated the frequencies that are giving offense as noisemakers, and have rated the magnitude of their offense in decibels—the acoustical doctor is provided with the basis for a diagnosis.

Sometimes a noise detector is used as a spy to keep watch on the mechanical condition of a machine. The huge 20,000-kilowatt turbines of the mercury vapor power plant at Schenectady were lately equipped with a device which records the noises generated when their steel vanes are spinning under the blast from boiling quicksilver. The clearance between rotating parts and stationary casing is a matter of only a few hairbreadths, and any undue expansion of the rotor or sagging of its shaft might damage the costly machine. So the listening device is installed (along with other electrical watchmen) to keep an ear on the

noises and give prompt warning if any unusual sound develops amid the normal bedlam.

A more common use of the sound meter is that to which it is put by the manufacturer of mechanical products, as an aid to "silent" designs. Today's electric fans operate with only a third of the noise which was normal to fans of 20 years ago; and electric refrigerators, washing machines, vacuum cleaners, and other appliances have lately suffered the loss of some of their customary operating noises. The tick of the bedroom clock has been softened. Air passengers of the 1920's were accustomed to stuff their ears with cotton before entering a plane for a flight; such insulation is no longer necessary, and noise meters report that the new "soundproof" cabins of the modern airplanes are not more noisy than an ordinary Pullman car.

The airplane cabin, however, can hardly be called a machine; its improvement in noise abatement cannot be credited to redesign of motors or propellers, but is primarily a matter of architectural acoustics. In particular it is the result of "treatment," by which is meant the use of sound-absorbing material in the construction of the walls, ceiling, and floor of the cabin. The same practice has been applied in the design or adaptation of larger rooms, and especially in the attainment of suitable auditoriums where the problem is not merely to exclude outside noises, but also to insure the most suitable interior conditions for the hearing of speech and music.

The foundations of architectural acoustics were laid 40 years ago by Wallace C. Sabine, as the solution of a practical problem referred to him. Dr. Sabine was Hollis Professor of Mathematics and Natural Philosophy at Harvard, and there had lately been added to the university's plant the Fogg Art Museum, which included among its rooms a large lecture hall. The hall was intended for use not only by art classes, but also by other groups that required a sizable room—but the very first speaker to lecture in the place

found the task almost insupportable. Let a sentence be spoken from the rostrum, and its syllables reverberated repeatedly. Sounds became a jumble; hearing was almost impossible. The problem of disentangling the waves seemed one for a mathematician and a natural philosopher, so President Eliot turned to Professor Sabine and asked him what could be done.

Broadly speaking, there are only two variables affecting the internal acoustics of a room: its shape (including size), and its materials (including furnishings). Dr. Sabine dismissed consideration of the first, for it was not practicable to alter the room's shape or size. But the materials of its surface might be changed, and so he began a series of experiments in that direction.

Three consequences may befall sound as a result of its collision with walls or other surfaces. The surfaces may *reflect* the waves, in which case there is reverberation. Or they may *transmit* the waves, and then the sound is heard in adjoining rooms. Or they may *absorb* the energy of the waves, and thereby swallow up the sound. Dr. Sabine found that the smooth hard surfaces of the plastered masonry walls and of the ceiling, floor, and varnished seats of the lecture room absorbed very little; they transmitted practically none, but they were very effective reflectors. When a word was spoken in an ordinary tone, the sound continued to be heard for more than 5 seconds while it reverberated between opposite surfaces. Even a slow speaker would have uttered a dozen or more syllables in those 5 seconds, and it was easy to understand that the ensuing mixture of primary waves with a succession of reflected waves would jumble to make hearing difficult.

The professor set up an organ pipe as a sound source of constant pitch and loudness, and installed a suitable chronograph for recording duration. When the pipe was intoned in the empty lecture room and suddenly stopped, the chronograph showed that 5.6 seconds elapsed before the

sound faded to a millionth of its original strength—the point at which sound is rated inaudible. This period he defined as "time of reverberation." Could it be shortened by the simple expedient of covering some of the hard surfaces with softer, more pliable material?

As the material for his experiment Dr. Sabine borrowed all the cushions from the seats of near-by Sanders Theatre. Some of these were brought into the lecture room and placed on its seats until a stretch of about 27 feet was cushioned; then the organ note was sounded, and in 5.3 seconds it had diminished to inaudibility. More cushions were added, enough to double the area of covered seats; and now the sound of the pipe died yet more rapidly, in 4.9 seconds. Additional cushions were placed until every one of the 436 seats was covered—and then the sound was audible only a small fraction beyond 2 seconds. Obviously he was on the right track.

More than a thousand cushions were waiting unused, and Sabine was determined to test their full effect. He carpeted the aisles with them, covered the platform, draped them on a scaffolding, cushioned the rear wall from floor to ceiling. When all were spread, absorption was so considerable that the sound lasted only 1.1 seconds.

Many of the tests were made in the quiet of night. They continued two years, and Dr. Sabine tried a variety of materials. The final outcome was a recommendation for resurfacing certain wall areas with felt. When this was done, as the professor modestly records the verdict in his final report, "the room was rendered not excellent, but entirely serviceable." It is still used; and while Harvard has built a new Fogg Art Museum and removed its exhibits and art quarters to the new and larger structure, one hopes that the old lecture hall may long be allowed to stand, for historical reasons if for no other.

Later investigators, with more sensitive and more exact tools of exploration, have added important refinements to

Sabine's work; but all modern achievements in the improvement of room acoustics rest on the foundations laid in the first Fogg lecture room. Reverberation time is recognized as a direct index to the acoustical quality of a room. And since the optimum time varies with the size of the room and the purpose for which it is to be used (music halls requiring, in general, a longer reverberation time than speech halls), the acoustical engineer has become an important ally of the architect. Too often he is not called into consultation until after the hall is built, but his art is such that by the use of "treatment" he may transform reflecting surfaces into absorbent ones, and by skillful placing of surfaces delete echoes, touch up dead spots, add resonance, and pretty well refashion a room into whatever acoustical pattern is desired.

The new Madison Square Garden, Radio City Music Hall, and Center Theatre in New York are examples of recent architecture whose acoustics were improved by the adept use of treatment. And for treatment the acoustician is no longer dependent on improvisations with cushions, felts, and other adapted fabrics. There has sprung up a whole new industry devoted to the manufacture of sound absorbents, and treatment may be bought in convenient slabs and blankets. The material must be porous or resilient, preferably both. And various ways of giving these qualities to a surface have been developed. One practice uses a hard smooth surface (of steel, plaster, or composition board) perforated with numerous small holes, and lays this over a blanket of rock wool or other soft fibrous material. The perforations in the hard outer surface provide pores to admit sound to the fibrous inner material whose resiliency and porosity are such as to absorb the waves.

Perhaps the most exacting practitioners of the new acoustical techniques are sound-picture recorders and radio broadcasters. In a studio of the Columbia Broadcasting System which I visited in New York half the room is

treated to provide sound absorption, and the other half is differently treated to provide a desired echo. The dead end, where absorption is 90 per cent, is the zone of hearing. Here the microphones are stationed. Here the floor is thickly carpeted, and walls and ceiling are lined with 4 inches of rock wool covered with perforated metal. This treatment was carefully planned to absorb all frequencies equally—an important desideratum, for some absorbents are selective, accepting high frequencies and reflecting the lows. The live end of the room is paneled in wood, and the panels are fastened only by their edges and so are free to vibrate. The absorptive and reflective areas of the studio are so proportioned and so placed with respect to one another that the sound waves striking the live end are thrown back to the microphone zone with a single reflection, and the vibrant quality of the wood seems to add richness and sonority to the reflected tones. The total effect is to increase the brilliance of music and speech. The designer explains this on the theory that the panels seem to act selectively as absorbers of confused sounds and as resonators of musically desirable sounds—damping those waves which are out of phase and reinforcing those that are in phase. Certain of the panels are set at slight angles to the vertical plane, care is taken that an absorptive surface faces each reflective surface—and by such ingenious use of treatment an excellent medium-sized room for orchestral broadcasts has been attained.

4

Sound absorption has been described as a surface effect, and until the present decade it was regarded as almost wholly that. But in 1930 Vern O. Knudsen, a physicist at the University of California at Los Angeles, was trying to calibrate a new sound laboratory there and chanced upon a strange behavior. He noticed that the acoustical properties of the room followed the vagaries of the weather. On

days when the wind blew from the Pacific, filling the laboratory with moist air, certain high-pitched sounds would reverberate 4 or 5 seconds. On other days, when the wind from another direction brought the air from the Mojave desert, the same kinds of sounds would reverberate only 2 or 3 seconds. It was the same room, the same surfaces, the same vibrations—only the air had changed. How could it make a difference?

Thereafter Professor Knudsen spent much of his time in pursuit of that question. First he considered the possibility that the atmospheric changes might affect room surfaces and so cause them to reflect more, or less, of the sound. To test this idea he applied successive coats of paint and varnish to the walls, ceiling, and floor, to make them impervious to moisture. But this surfacing made no difference—the weather continued to call the time. On a trip abroad Knudsen discussed his problem with European physicists. A German authority advised him to line the room with bathroom tile; then the anomaly would disappear, he said.

Before spending $2000 on this tile treatment the Californian professor thought he would try another experiment that might explore the difficulty less expensively. It chanced that the university possessed a smaller room, made, like the new laboratory, of concrete, and surfaced in exactly the same way—the only difference being that it was less than half the size of the new laboratory. From the dimensions Knudsen calculated that in the small room the sound waves would be reflected back and forth approximately 200 times a second, whereas in traveling the wider spaces of the large room only 93 reflections occurred. Thus, in 1 second a wave would be in contact with the surface of the small room more than twice as often as in the large room; and if absorption were only a surface affair it should proceed at a rate proportionate to the number of surface encounters and, therefore, should occur more rapidly in the smaller chamber. He was able to derive formulae for

the rates of sound decay in the two rooms; but when the test was made glaring discrepancies between theory and fact showed up. Experiment proved that the absorption of sound at the surfaces was in no wise affected by the humidity of the air, and indicated that the variations which had been observed were due to the absorption of sound by the air itself—that dry air took in certain sounds of high pitch, sucked them up as it were, while very moist air was far less absorptive and therefore would conduct the sound for greater distances.

All this was startling to the acoustical expert of 1930, whose science rested on the theoretical structure erected in the nineteenth century by Lord Rayleigh and his colleagues. According to their teaching the condition of the air should have very little effect on its conduction of sound. At that time Rayleigh worked out a set of equations to account for the behavior of sound, assuming it to be a wave form moving through a uniform continuous medium. Of course all knew that the air is no such isotropic jellylike stuff. Obviously it is a conglomeration of particles of different sizes and weights, the molecules of nitrogen, oxygen, and other gases. But, as Lord Rayleigh pointed out, the analysis of sound phenomena on the basis of particle collisions involved mathematical difficulties and, moreover, was not necessary. It was not necessary, he reasoned, because the departures of sound behavior in fact from the behavior pictured by theory were so slight that for all practical purposes they were negligible. The revolutionary effect of Knudsen's discovery is to show that for certain high frequencies the departures are not negligible, the actual air absorption in some cases being 100 times greater than that predicted by Rayleigh.

The California experiments demonstrated that both humidity and temperature affect sound absorption. The influence of temperature is steadily progressive. Cold subzero air is practically transparent to sound, but with heat

the air becomes increasingly absorptive until at high temperatures it is so opaque to high-pitched sounds as to make the latter inaudible at a distance of a few feet. In the case of humidity this progressive relationship does not hold. Perfectly dry air is the most transparent acoustically, air containing a pinch of moisture (about 10 to 20 per cent relative humidity) is the most opaque, and thereafter with added moisture the ratio of absorption decreases until at 92 per cent relative humidity the transparency to sound is almost back to the maximum. This latter condition corresponds to the moist fog-laden air of the ocean, while air which is only 20 per cent humid approximates that of the desert.

Many phenomena of nature are illuminated by this discovery of the influence of atmospheric conditions on sound. In the Arctic it is not uncommon for two men conversing in the open to be heard over the icy wastes for distances of 4 miles, and the barking of dogs has been heard 15 miles. It was the custom to explain these long-distance sounds as a consequence of the reflection of sound waves back to the ground by certain upper-air strata, but it seems likely now that the Knudsen effect provides at least part of the explanation. Desert travelers are familiar with the sound blanketing of hot, almost moistureless air.

Nor are these findings only of academic interest. Dr. Knudsen points out that in a large hall the reverberations of high frequencies of speech and music may be affected more by the conditions of the air than by the nature of the surface materials. Consider, for example, sound at a pitch of 10,000 cycles, a frequency within the range necessary for high-quality music. If the air of an auditorium were at 70°F. and of only 18 per cent relative humidity, sounds of that pitch would be absorbed by the air so rapidly that, even with totally reflective walls, ceiling, and floor, the sounds would decay in ⅝ seconds. The inherent absorption by the room boundaries, including the audience, would reduce

the time of reverberation to less than ½ second. Admittedly this air is drier than is customary, but even with a relative humidity of 50 per cent the reverberation time would be less than a second—a duration too brief for good musical effect. Not only surface treatment but also humidity and temperature control may be important considerations in the acoustical engineering of the next 10 years. Designers of sound-reproducing equipment for use in large theaters and out of doors may need to take into account the absorptive characteristics of air, and also those who plan to use sound in distant signaling, in altimeters for aircraft, and in fog warnings.

From his discovery of this curious effect of moisture and temperature on the acoustical properties of the air, Knudsen was led to dissect the air into its gases and investigate these separately. He found that when a small pinch of moisture is introduced into an atmosphere of pure oxygen, the ratio of sound absorption is five times greater than that of air containing an equal proportion of moisture. But when the same amount of moisture was introduced into pure nitrogen there was no increase in the sound absorption.

So it is the oxygen in our air, and not the nitrogen, that is responsible for the greater part of the sound absorption. If our atmosphere contained no nitrogen, but were made up wholly of oxygen with such admixtures of water vapor as are common, it would be difficult to hear a message across the street. The high-frequency components of speech—such consonant sounds as *th*, *s*, and *m*—would be swallowed up within 50 or 70 feet. Knudsen's later studies of other gases show that carbon dioxide is even more absorbent than oxygen. Conversation in an atmosphere of carbon dioxide would require the voice of Stentor, for the high-frequency consonants would be absorbed within a few feet.

The explanation of these newly discovered acoustical qualities of gases seems to lie in the varying characteristics of collisions between the gas molecules. The progress of a

sound wave shakes the air into a succession of contractions and expansions, molecule is bumped against molecule, and into the thermal movement of particles which is characteristic of the gas there is injected this additional periodic agitation. We used to think that the colliding molecules would behave approximately alike so far as their influence on sound is concerned, but Knudsen's work shows that uniformity does not exist. Roughly, it is as though a billiard player who has been pursuing his game on the theory that all the balls are of hard ivory should suddenly discover that some of the balls are of soft rubber. A rubber ball takes the energy of a collision differently from an ivory ball, and similarly the interaction of an oxygen molecule in collision with a molecule of water vapor produces a result different from that of nitrogen colliding with water vapor. Still different is the effect of carbon dioxide collisions. What we are dealing with in these collisions is a chemical phenomenon, for it appears that certain gases have preferential affinities, and in the bouncing of molecule against molecule temporary combinations are formed whose duration is different for different gases. These temporary compounds, of oxygen and water vapor, for example, or of carbon dioxide and water vapor, may endure for only a small fraction of a second and then break apart into their constituent molecules, but their temporary linkings are sufficiently potent to take up some of the energy of the sound waves and thereby to absorb or diminish vibrations.

Several scientists have made important contributions to the theory of this new-found behavior. Among others H. O. Kneser, of the University of Marburg, has worked out a mathematical analysis. Professor Kneser shows that the energy transitions which occur during these collisions and partnerships must be reckoned in terms of Planck's constant h, the immutable constant of action which figures in the quantum mechanics of the atom. Sound-absorption measurements thus provide a means of determining the

reaction constants of gases, and these give important information regarding the nature of molecular collisions. Thus the research scientist finds in the Knudsen effect a new tool of exploration, a means of prying into the minute mechanics of gases.

So important is this discovery, so fundamental to the advancing front of physical knowledge, that at its Christmas week meetings of 1934 the American Association for the Advancement of Science awarded its $1000 prize for the year to Professor Knudsen. He is continuing his researches at the laboratory in Los Angeles, where he has fitted up a 2-foot cubical steel box as his reverberation chamber. With that more compact and convenient apparatus he is pursuing fresh explorations into this novel borderland where physics merges with a new chemistry.

Chapter IX · CHEMISTRY ADVANCING

Chemistry is not merely a great science among other sciences, but a science which pervades the whole of life.

—ARTHUR JAMES BALFOUR

TEN thousand chemists gathered in New York in 1935 to celebrate the three-hundredth anniversary of the establishment of chemical industries on the American continent. It was, so statisticians said, the largest gathering of scientific workers ever assembled in the United States—and appropriately so, for chemistry is basic to our industrial civilization and the chemists constitute our largest group of technicians.

They are more than technicians. They are what some of us, more apt in phrase making than in quantitative analysis, are inclined to call doers of the impossible. For it is of the practical applications of chemistry, rather than of its theoretical principles and fundamental discoveries, that our thoughts first turn. We are still of a mind akin to that of old John Adams, in his address to practitioners of his day: "Chymists! Pursue your experiments with indefatigable ardour and perseverence. Give us the best possible Bread, Butter, and Cheese, Wine, Beer, and Cider, Houses, Ships and Steamboats, Gardens, Orchards, Fields, not to mention clothiers or cooks. If your investigations lead

accidentally to any deep discovery, rejoice and cry 'Eureka!' But never institute any experiment with a view or hope of discovering the first and smallest particles of matter." One cannot say that the chemists have taken President Adams's oracular warning seriously. For while it is true that many of their deep discoveries have been hit upon by accident, it is also true that many more, and perhaps the most important discoveries, have been the rewards of planned expeditions into the realm of the first and smallest particles of matter. The three American scientists whose work has been recognized with a Nobel Prize in Chemistry each deliberately blazed a trail into the microcosmos: Theodore W. Richards, by his careful atomic weighing of elements; Irving Langmuir, by his exploration of the invisible flatland of monomolecular films; and Harold C. Urey, by his discovery of the double-weight hydrogen atom. Even so, it is the mundane tendency of the lay mind to evaluate the chemists for their practical achievements. We too subconsciously bracket them with clothiers and cooks. And also we are inclined to rate their bread, butter, and cheese above their protons, neutrons, and deuterons.

Perhaps this utilitarian attitude is the most instinctive approach to modern chemistry, even to its borderlands. The alchemy which fathered our science was a very utilitarian pursuit of two practical desires of mankind: first, the almagest, by which wealth might be attained from baser materials; and second, the elixir of life, by which age and death might be defeated. In a certain sense these two pursuits are still dominant objectives of chemistry. In later chapters mention will be made of current work of the biochemists, and some accounting given of the modern search of the mystery of life, of aging, and of death. Here we shall dwell more particularly on the wealth winners: such realists as those who have snatched unwilling nitrogen out of the air to fertilize agricultural fields, those who have

spun forests into fabrics finer than silk, those who have made rubber in a test tube without benefit of Brazil or the East Indies—to mention but three of the long roster of alchemical retrievers.

I

There is, for example, the incident of the floating laboratory. This was an old ship equipped with the necessary apparatus, manned with a staff of chemical engineers, and sent to prospect the ocean. For months at a time it was out there, pumping water through an ingenious chemical sieve, picking off certain preferred molecules from each gallon, and pouring the residue back into the ocean. At the end of their prospecting the sea miners had extracted a few hundred pounds of bromine at a cost of $500,000—which would seem to imply that bromine might be rated as a new substitute for gold.

But not so. Bromine is indispensable to the manufacture and use of no-knock gasoline; and because of the mounting demand of motorists for the improved fuel, it was necessary to look for new sources of supply. The old brine wells were failing, new ones were not being discovered, and in this dilemma the industrialists turned to that universal treasure trove, the sea, which contains all things in solution. Analysis shows that about seven millionths of each drop of sea water is bromine. But was chemistry able to extract so minute a fraction at a reasonable cost?

The floating laboratory and its prolonged experiment answered that question. Today a commercial plant for extracting bromine from the Atlantic Ocean is in operation on the North Carolina coast. It is turning out thousands of pounds a day. And since each cubic mile of sea water contains some 600,000 tons of the element, there is no danger of the factory ever being short of raw material.

This success suggests another question. Since the sea contains all things in solution, why not mine other sub-

stances too? Gold, for example, is selling for $35 an ounce, whereas bromine is quoted at less than 2 cents an ounce. Is there any gold in the sea?

Yes, and this North Carolina bromine plant has already extracted minute quantities of it and other precious metals. At a recent meeting of the American Chemical Society one of the engineers exhibited particles of pure gold and pure silver which had been taken from the flood of Atlantic water sluicing through the bromine extractors. The sea gold is dilute. A gallon of Atlantic water contains only one thirty-thousandth as much gold as it contains bromine, and of course the gold did not drop out of the water obligingly. It had to be captured by delicate processes which cost ten times the present market value of the gold. But the point is that the thing has been done—and what is done at great effort and expense now may be accomplished more easily and economically next time. Indeed, the chemist who attained this sea gold predicts that within our century we shall be mining the ocean for it on a commercial scale.

2

Getting a scarce product from a difficult source is one thing. Improving the product or making an entirely new one is another—and these doers of the impossible are versatile.

Take glass, for example. The very first characteristic of glass that occurs to you is its fragility. It is, traditionally, something to be handled with care. But in a research laboratory I saw a man tossing a glass lens into the air and allowing it to fall on a concrete floor. Indeed, the performance seemed to be a game to see how hard he could drop the glass. Repeatedly the lens fell from a height of 10 feet without even chipping. And this lens was not fabricated of thin laminated sections like an automobile windshield; nor was it reinforced by wires or any other mechanical aids. It was a solid piece of clear optical glass—tough glass that can be broken if you insist on it, but your

blow must be thirteen times as great as that required to break a similar lens of ordinary glass.

The chemists make this tough glass by violating a long established rule of factory practice. The conventional idea is that after a piece of glass is poured or cast, it must be cooled slowly. But this tough glass gets no such babying. It is plunged from a heat of 1500° into a bath of oil at 400°, and by that sudden change of temperature the toughness is imparted. The exterior layer solidifies before the interior does; and in the slow contraction of the interior, tensions are set up which oppose and counterbalance exterior blows.

By another new process, glass is being spun into fibers soft as eider down. "Glass wool" is an old story, and has been used for many years as a packing for heat insulation and even woven into fabrics for hats, dresses, and scarfs; but this new fiber is glass in a new physical form, so fine that it is almost all surface, and yet so strong that it possesses a tensile strength approaching that of steel. The fibers are obtained by a process somewhat similar to that used in rayon manufacture—the molten glass is forced from tanks in fine filaments, the pressure being so great that the glass spurts out at a speed comparable to that of a rifle bullet. In addition to the customary uses of glass wool, many novel and indeed amazing applications of the new fiber are in process of development. It gives every promise of being a material with a future.

Glass suggests building materials. Glass brick and glass paneling and glass columns are now on the market, and houses with a wall or a roof of glass have been constructed. Chemists have added to glass the ability to filter the solar heat rays and transmit only the rays of light; so a glass house may be cool. And it may be proof against the stone thrower too, for toughness is not confined to optical glass. As a test a 3-ton truck was driven upon a 1-inch-thick sheet of this glass, a cable was passed about both, and the whole lifted high by a crane. The glass bent, but did not break.

3

Also just out of the laboratory are artificial stones and artificial woods made of waste, stainless metals made of new alloys, synthetic resins fashioned out of new chemical combinations. A typical example of the last named, and also of the skill of modern synthetic chemistry, is vinylite, developed at the Mellon Institute in Pittsburgh.

Visitors to the Century of Progress Exposition will remember the three-room apartment molded entirely of this new stuff out of a test tube: the floors of vinylite tiles, the walls of vinylite panels, the baseboards, sills, ceiling, all of the same; each door a single piece of vinylite, cast and pressed into shape; even the windows a translucent vinylite. More recently the applications of this material have been widely extended. It is possible to have whole tables, desks, chairs, chests, and other articles of furniture molded of one piece. And there are other plastics—some remarkably transparent like glass. The transparency of the new lucite, reports a chemist, "puts it on the same plane as quartz or the finest crystal." Some of these clear unbreakable glass-like plastics are lightweight, suggesting their adaptability for airplanes, automobiles, railway coaches, and other places where ruggedness and light weight are esteemed.

One of the objectives of modern chemical research is a cheap method of processing common clay for aluminum. Our present source of supply for this metal is bauxite ore, the deposits of which are closely held. But aluminum is one of the most abundant elements in the Earth; it is found in ordinary clay, which is widely distributed; and the unlocking of that plenteous source should make the metal cheaper. Then we may expect a rapid multiplication of its uses, which already are legion.

Aluminum of itself is relatively soft, but when alloyed with small proportions of other metals it becomes extremely hard and durable. These alloys, which received their first

substantial encouragement from the aeronautical designers, are now stepping over the lines into all sorts of industries. Factories have discovered that the heavier a crane is in proportion to its strength, the less load it can carry—so they are making giant cranes of aluminum alloy. And those swift streamlined passenger trains! They can be credited to the chemist's crucible quite as much as to the engineer's slide rule, for there is hardly a material in the new trains which did not come out of recent research. Locomotive parts are being built of lightweight alloys. One train of three cars weighs no more than a single Pullman car of the old all-steel construction.

Alloys in bewildering variety are on the horizon, and metals that were laboratory curiosities a few years ago are rapidly coming into useful service. Cadmium is threatening the supremacy of zinc. And also titanium—its pigments are taking the place of the familiar zinc in paints and rubber. The little known metal indium is substituting for silver as a mirror material. Tantalum, gallium, and germanium are making important beginnings in industrial applications, and in another 10 years these rarities will be commonplaces. The metal sodium (an ingredient of common salt) is a better conductor of electricity than copper—and the electrochemists are playing with that fact in researches that may prove revolutionary. Recent discoveries of the properties of skins of metals have given the chemist new and powerful means of adding durability, protecting against corrosion, and testing for invisible flaws. Surface effects of magnetism, x-ray reflections, and spectroscopic analysis have become tools of the metallurgist in applying the chemistry of metals to the multiplying uses of our age of speed.

But our age of speed glides forward not only on the new alloys, but also on the new fuels which chemists are obtaining from coal, petroleum, and wood. The process of cracking the heavy oils and other residue of petroleum, after the normal stores of gas and gasoline are extracted, is adding

many millions of barrels of fuel to our use. In the cracking stills, the heavy residue (material that in other days had to be disposed of as waste) is subjected to high temperature and enormous pressure. The combined effect is to "crack" the large molecules into smaller ones, and some of the small molecules turn out to be gasoline, others to be a fine grade of furnace oil, others to be gas. By distillation each of these products is separated out, including not only fuels but other molecular structures which form the raw material for synthetic processes of making alcohol, lacquers, plastics, and rubber substitutes.

By another process or series of processes, which the chemists call polymerization, combustible gases are caused to combine into molecules of gasoline. And this synthetic gasoline is so uniform chemically, its molecules are so nearly the same throughout in structure and energy content, that the control of combustion in engine cylinders is greatly enhanced over that of the old natural gasolines. This enhanced control makes possible important improvements in power output and fuel economy. Since the raw materials of the polymerization processes are the gases which are yielded up as by-products of the cracking process and the dissolved gases derived from crude oil, natural gasoline, and natural gas industries, the new techniques of the polymerizers are powerful factors in getting more and more gasoline from our present raw materials. Recent estimates by Gustav Egloff suggest that 9000 million additional gallons of American gasoline can be obtained annually through these means. Therefore the new techniques are to be hailed as agencies of conservation.

The transformation of coal into gasoline—a process which is now operated on an industrial basis in Germany—was demonstrated in the United States in 1936 at the Bureau of Mines in Pittsburgh. Here, in a small experimental plant, powdered coal is treated to high pressures and high temperatures and exposed to hydrogen gas. In the mauling and

mixing of the molecules some of the hydrogen atoms combine with the hydrocarbons of the coal to form the larger molecules of fuel oil, gasoline, or gas—for it is possible by varying the treatment to transmute the coal into any selected one or more of several products. Hydrogenation, as the process is called, is more costly than our present processes of refining crude oil and cracking its residues; and there is no call for coal hydrogenation in the present stage of American economy. But the Bureau of Mines looks ahead to the approaching exhaustion of the petroleum reserves. Some authorities estimate that by the early 1950's the underground pools, which made North America the greatest petroleum producer, will have been exploited to the limit of economical extraction. Then the automobiles, airplanes, and other vehicles and utilities powered by explosive motors will have to look to other sources for fuel. The coal fields of the United States are many times more prolific than the petroleum fields. A. C. Fielder recently computed that if all the present proved petroleum supplies of the United States were spread over the state of Ohio they would cover its 41,000 square miles to a depth of ¾ inch; but if all the coal deposits were similarly distributed over the same area they would make a layer 76 feet deep. There is fuel here for hundreds of years of accelerating industrialism.

Frederich Bergius, the German chemist who developed the hydrogenation process of converting coal into oil, is also author of a process of converting wood into food. Dr. Bergius's method rests on an earlier discovery by two other German experimenters, Willstätter and Zechmeister, who found that the cellulose extracted from wood will completely dissolve if submerged in a strong solution of hydrochloric acid, and that while in this solution the cellulose "transforms" 100 per cent into glucose sugar. What happens in the fluid is the merging of one molecule of water with one molecule of cellulose, the sum of the two being sugar; and because of this the process is called wood

hydrolysis. But cellulose is only one ingredient of wood, and to separate it from the hemicelluloses, lignin, and other constituents of raw timber involves a costly preliminary process. The great achievement of Bergius is the application of the process to raw timber. The log ends and other refuse of logging, the sawdust, slabs, shavings, and other wastes of the lumber mill, whole trees or parts of trees as may be available, all are grist for Bergius's chemical mill. It converts the wood into digestible carbohydrates of the sugar type, to the extent of from 60 to 65 per cent, and even the fibrous residue is material for charcoal, wallboard, and other by-products. But the food derivatives are the prime objective, of course, and from the simple sugarlike products other foodstuffs may be obtained.

Thus, "the carbohydrates consumed by pigs will form fat," points out Dr. Bergius. "With a suitable yeast, protein can be produced from hydrolized wood solution. Crystallized glucose produced from the wood can supply a considerable amount of edible carbohydrates necessary for nutrition. In other words, it is possible to produce practically all the fundamental elements of nutrition from waste wood. This can be done without reducing the forest reserves, because the waste of the lumber production can supply enormous quantities of raw material for wood hydrolization. The process is not only suited to supply foodstuffs to countries lacking such, but also gives an opportunity to turn a waste product into something useful."

Here is an even more adept chemistry than that of the Brobdingnagians who made two blades of grass to grow where only one grew before. Nor is it only a project, a prospectus of possibilities: it has been done, and is in practical use today.

4

The achievements in fundamental chemical research are not so obvious as are the applications wrought in the indus-

trial laboratories; they are not expressible in terms of added conveniences or lowered costs or utilized wastes, but I assure you they are preeminently important to the future of mankind—that is, if we may judge the future by the past. The very foundations of thought are in process of change. America is contributing to this revolution. The fact that twice within the 1930's the Nobel Prize in Chemistry has been awarded to a citizen of the United States is fairly circumstantial evidence that the science is alive and fructifying on these shores. Science is international, and planetary rather than continental, and I would not inject into this account any specious parochialism. But too long the chemical researchers within the United States have appeared to be preoccupied with profitable applications, and it is worth noting that fundamental discoveries are now increasingly rewarding seekers who "have no time to make money." Nor do the fundamental finds remain merely interesting curiosities very long. A recent *Industrial Bulletin* of Arthur D. Little, Inc., calls attention to the fact that heavy hydrogen, a discovery of 1931, has already shown a quality foreshadowing important industrial uses. The energy density of this rare variety of hydrogen, it seems, is enormously great. With this gas, jets of such high velocity are produced that the energy available in 1 pound of heavy hydrogen, and attributable to the speed alone, is equal to that obtainable from the combustion of 5 million pounds of coal.

Heavy hydrogen and its consequence, heavy water, are only the headliners among a horde of isotopes and compounds recently turned up in the pursuit of knowledge for its own sake. And these pioneering chemists—many of them mere youths in their twenties and thirties—are pressing the merger of physics and chemistry closer and ever closer with their applications of the new-found principles to chemical practice. We are coming into a new technique, the so-called quantum chemistry. Here chemistry emerges

from the hit-or-miss of an empirical science to the attainment of a reasoned logic in which properties and behaviors are calculated and predicted. This new chemical competence rests on the surer knowledge of atomic structures and forces which recent research has brought, enabling the chemist to foresee not only the possible combinations, but also the speed and order with which the reactions will occur.

Let us consider the item of speed. Life itself is one phase of this engaging question, as the Princeton chemist Henry Eyring has pointed out, and I am quoting from a recent paper of his to illuminate our curiosity about chemical speed. "For molecules to combime to form new ones, they must collide with catastrophic violence," says Dr. Eyring. "The atoms in the two colliding molecules must approach so closely that they no longer know whether they are bound to the new or the old atoms. For convenience, this is known as the activated state. If these violent encounters occur once in every million million collisions, the reaction goes moderately fast. But if they go faster, say once in every thousand million collisions, an experimental chemist will be unable to distinguish between this rate and reaction on every collision. He will simply say in either case that the reaction goes immeasurably fast. By cooling his vessel he slows down all the molecules and can so cut down his rate to something measurable. Thus, simply by observing how a chemical reaction changes with temperature, he can tell you how violent a collision must be in a particular case to cause reaction; but, until the last 3 or 4 years, he could not even guess how violent a new type of collision must be to bring about a reaction. This the quantum mechanics has completely changed. He can now calculate, as accurately as he pleases, how energetic a collision must be to cause chemical change, and, therefore, at what temperature it has a measurable rate. Moreover, approximate calculations, which are simply made, frequently tell him which of two reactions will go the faster. This is a type of question which

to answer experimentally frequently requires a great amount of time and great expenditures of money. For the exact calculations one needs no other data than the laws of quantum mechanics and the fact that one is dealing with a certain set of charged particles, and all the physical and chemical properties emerge as a matter of course."

This new precision seems very far removed from the chemical pioneering of 300 years ago. It was in 1635 that the science obtained its first foothold in the New World. In that year John Winthrop, Jr., a young alchemist of the Massachusetts Bay Colony, visited England and obtained from the Crown a commission to develop certain native mineral resources. He was interested in the production of copper, glass, iron, lead, tar, and other "chymicals" including medicines—no mere dreamer, this alchemist! The Royal Society later asked him to see if the grain, American maize, would produce beer. Winthrop tried it and brewed a "pale, well-tasted middle beer." He even did research on cornstalks and found that they yielded "syrup sweet as sugar"—a foretaste of the extensive corn-syrup industry of today.

Winthrop's projects were primitive, his incentives appear to have been wholly commercial, his research strictly industrial. There was, in the year of his commission, not a college or university, not a laboratory or other scientific institution of any kind, in the Colonies, and indeed only the most fragmentary approaches to science in Europe. But out of these practical seekings chemistry grew, in knowledge and stature and wealth. It is interesting to reflect that the two American fortunes which have contributed most largely to the equipment and support of scientific research are founded on chemical industries—the Carnegie fortune on the steel industry, which received its greatest acceleration from Bessemer's process of promoting the chemisms of steelmaking, and the Rockefeller fortune on the petroleum industry, which is so directly indebted to Willard Gibbs's

discovery of the phase rule as the foundation of physical chemistry. The Mellon fortune derived much from Charles M. Hall's application of electrochemistry to the extraction of aluminum, and in turn it has fostered many industrial researches to useful and successful fruition. Chemistry has been described as creative, but more aptly it may be characterized as a catalytic agency, activating industry, wealth, the other sciences—civilization.

Chapter X · A CHEMIST ON VACATION

> The chymists are a strange class of mortals impelled by an almost insane impulse to seek their pleasure among smoke and vapor, soot and flame, poisons and poverty, yet among all these evils I seem to live so sweetly that may I die if I would change places with the Persian king.
>
> —AN OLD ALCHEMIST

THE story of chemistry is not only the record of man's measurement and manipulation of the ninety-two chemical elements, and of their combination, activation, and other manifestations. There is also a subjective side to this discipline, an aspect of science as human endeavor. Man the measurer is also a living soul, with hopes and incentives, touched by inscrutable intuitions, moved by thoughts that in other times or other personalities attune the spirit to poetry or music or worship, "thoughts that do often lie too deep for tears;" and the "dear delight" of discovery invariably outweighs its richest fruits. There is indeed an aesthetic element in the pursuit of science that only its intimates know. Nietzsche held that the scientific man is the finest development of the artistic man. Leonardo da Vinci esteemed his scientific accomplishments above his paintings and other art. "If Shelley had been born a hundred years later, the twentieth century would have

seen a Newton among chemists," says A. N. Whitehead. Indeed it is poets and artists and dreamers that we approach when we visit the laboratories, with the added distinction that these visionaries so often are able to see their poems and art and dreams come true.

Some of the dreamers—astronomers, cosmologists, world builders—take the Universe as their province, and seek to comprehend the all in one inclusive system. Others—and perhaps they are the more ambitious—look closer. They probe among the invisible molecules, break these chemical structures into their atoms, blast the atoms down to their invisible parts, and try to read in the microcosm the eternal riddle of a world and a life and an intelligence. Irving Langmuir is of this latter group. He chose a trail into the infinitely little as his way of satisfying the great curiosity, and out of that highly specialized pursuit has come new light on familiar mysteries, a new understanding of fundamental phenomena, a whole new branch of science. New industries, new factories, new products, new conveniences, as well as new ideas, emerged from his findings—yet he had no practical end in view when he entered upon the search.

Indeed, the whole remarkable venture began as a summer vacation. Langmuir was a teacher of chemistry who varied the monotony of pedagogical tasks with summers of mountain climbing. In 1909, however, an opportunity opened to spend July and August in a research laboratory. The vacation then begun has continued more than a quarter century, for he never went back to his classroom, but stayed on in the laboratory, fascinated by an experiment. It led to other experiments, and discovery followed discovery as he brilliantly pioneered new frontiers of knowledge, blazing "paths where highways never ran," often a solitary figure, exploring, experiencing, satisfying his soul. From such preoccupations he was called to Stockholm in 1932 to receive the Nobel Prize in Chemistry.

I

A search of the Langmuir pedigree reveals no scientific forebears, unless we count a maternal grandfather who was a New England physician. Irving Langmuir's father was a businessman, self-made in the sense that he hired out as a clerk at the age of fourteen and by the time he was thirty-five had accumulated a comfortable fortune. Then, soon after the birth of his fourth son, he lost it all and more in a mining venture, and much of the remainder of his life was a period of financial struggle. During his last 6 years he was agency director for Europe of the New York Life Insurance Company; the European post gave the family advantages of travel and of cosmopolitan contacts; but the four boys grew up in this atmosphere of struggle, and it colored their life with a sense of serious purpose. There was Dean, the youngest; Irving, 6 years older; next, Charles Herbert, who was 5 years older than Irving; and the eldest, Arthur, whose preoccupation with chemistry was to turn Irving's interest in that direction.

Perhaps the most definite tendency of science in the household was the disposition to record accurately and systematically whatever went on within the domain of the family. Charles Langmuir, the father, began a diary in his early manhood. He also kept a cashbook recording in double entry every day's financial transactions, even to the purchase of a penny newspaper or the payment of a boot-black. He kept a separate record of his travels, the itinerary, the hotels visited, the number of the room he occupied in each. Sadie Comings Langmuir, the mother, was almost as keen as her husband for record keeping. She too treasured the day's events in a diary, and instilled the habit in her sons. She encouraged them to write detailed accounts of their travels, experiences, and observations.

When he was eleven years old, living with an aunt in his native Brooklyn, Irving Langmuir wrote his mother, in

Paris, of a project that was engaging his attention. The definiteness of the detail is characteristic.

"I am building a windmill which is going to be about 3 feet high and 1 foot wide at the bottom and 6 inches wide at the top. The wheel is going to be like this. [The letter contains a sketch.] The wheel's axil is going to be made of wood with pieces of tin this shape [another sketch], each one being about 3½ inches long. The whole wheel's diameter will be about 8 inches. I have two sides all done and the other two sides half done of the tower part."

Within a year the family were settled in Paris—the insurance company's headquarters were there—and soon after Irving's thirteenth birthday Mrs. Langmuir was writing to a friend in America: "Irving's brain is working like an engine all the time, and it is wonderful to hear him talk with Herbert on scientific subjects. Herbert says he fairly has to shun electricity, for the child gets beside himself with enthusiasm, and shows such intelligence on the subject that it fairly scares him."

A tireless stoker of this scientific flame was Arthur, who by now had completed undergraduate studies at Columbia and was entering Heidelberg for a postgraduate course in chemistry. There were many letters back and forth between the two. Irving, eager to try the experiments which his brother outlined, was delighted to have access to the laboratory of a small boarding school in a Paris suburb where he had been entered. One of the teachers encouraged the thirteen-year-old to use logarithms and to solve problems in trigonometry. He delighted in these extracurricular activities. But most of his time in the French school was spiritual torture to the sensitive boy. The absurbly rigorous discipline and the inflexible system of learning by rote stifled him. Until he was fourteen he "hated school, and did poorly at it," to quote his own recent estimate of that period.

In his fifteenth year he returned to America and entered school in Philadelphia. The following year Arthur, who was

now starting out as an industrial chemist, married, and Irving came to live in his brother's home while attending high school in Brooklyn. Here the boy taught himself the calculus. He knew so much chemistry that the school excused him from attending classes in the subject. He fitted up a laboratory at home and learned qualitative analysis under Arthur's tutelage.

When Irving Langmuir enrolled in Columbia University, it was to become a candidate for the degree of metallurgical engineer, in its School of Mines, though he had no intention of practicing metallurgy or mining. "But the course was strong in chemistry," he explains, "it had more physics than the chemical course, and more mathematics than the course in physics—and I wanted all three."

Judged on usual collegiate standards, Langmuir's four years at Columbia would be rated a failure. He "made" no clubs or teams, took no part in athletics, never "went out" for one of the university papers, was not invited to join a social fraternity or to serve on a class committee. Outside classrooms and laboratories, the teeming university seemingly was unaware of his existence.

The professors showed little intuitional ability to spot a future Nobel laureate. The intense, eager youth was never invited to any of the professorial homes for an evening's chat. Dr. R. S. Woodward, professor of mechanics, one day posed this question to the class: "If you could do what you want most to do, what career would you choose?" When the question came to young Langmuir he answered, "I'd like to be situated like Lord Kelvin—free to do research as I wish." This touched some resonant chord in the professor. He encouraged the ambitious junior to consult him, and occasionally there were long talks between the two after class. "Professor Woodward suggested many interesting problems," recalls Langmuir, "which I loved to work out—for the fun of it." He was graduated in June, 1903, with an average grade of 94 per cent.

The following autumn the "metallurgical engineer" enrolled at Göttingen for advanced studies in physical chemistry under Walther Nernst. During the three ensuing postgraduate years in Germany there was considerable debate in the young scientist's mind, and by letter between him and his brothers, as to his future. Should he go into chemistry commercially, or should he aim for the more rarefied heights of scientific research? I am privileged to quote a letter he received at this time from his brother, Charles Herbert:

"The whole matter resolves itself into the question whether you have, or have not, exceptional ability in pure science research. If you simply have a well-grounded knowledge and a thorough efficiency, you should certainly go right into the business of chemistry, where you can be of most use to yourself and everybody else. But if you are the exceptional man, it is, in my opinion, your duty to be one of the pioneer scholars in America. . . . The time has come when this country must have her distinctive scholars. If they do not get great honor now, they surely will by the time you have done anything particularly worthy. Meanwhile, you will have the incalculable advantage of a great aim with all that it contributes to happiness and the full life. . . .

"There is a great deal that is noble and inspiring in business, and business can always be conducted in the better way, but it is a lower thing for some men than research and scholarship. Most of us are suited to nothing else but business, not being finely enough organized mentally to spend our careers in other than active work. But perhaps you are one of the few with creative brains. If you are (and don't decide so unless you have good authority) you will betray your true self if you devote your life selfishly to private enterprises and personal acquisition. And the minute you allow yourself to deviate from the path of pure science, you will lose something in character, and

more still in the power to aspire and the possibility to be truly happy."

This was in 1904. At that time no Nobel prize had come to any American, though in Europe more than a dozen scientists had received this supreme accolade. Just that year Lord Rayleigh had been named as the prize man in physics and Sir William Ramsey in chemistry, a double recognition of their joint discovery of argon—that strange rare gas which Langmuir was destined to harness to the purposes of man. Whether there entered the mind of the young American in Göttingen any thought of his own future in possible association with a Nobel prize, I do not know. But when he came home in 1906 he had decided to risk a career in scholarship, and had accepted appointment as instructor in chemistry at Stevens Institute of Technology in Hoboken, New Jersey.

It is interesting to speculate on the "ifs" of the past. What might have been this man's life if Columbia had discerned his latent powers, and had installed her brilliant unknown in line for one of her chairs in science? Or if Stevens had recognized the genius of research who was pacing away his hours trying to teach sophomore engineers the rudiments of chemistry? He had a difficult time there. Teaching, with its demand for a disciplinarian and its interminable piles of papers to be graded, was a chore. One remembers Whistler serving as draftsman in the Coast Survey office, and Charles Lamb poring over the ledgers of the London accountant.

With his brother Dean, Irving used to take long walks along the Palisades and into the highlands of the Hudson, and the talks that enlivened these jaunts are forever memorable to the younger man. Usually the theme was some subject of science, frequently an interpretation of familiar phenomena. A rainbow, a raindrop, an oil film on a pond—these are worlds of beauty and orderliness and meaning to Irving Langmuir. I have seen him poise a soap bubble

to point out its dark monomolecular area that exists for an instant just before the bubble bursts. How resonant his voice, how vibrant as he rises to some peak of exposition, like a mountain climber who has guided you up his favorite height to point out his favorite view.

He might have gone mountaineering again that summer of 1909 but for a meeting of a scientific society in Schenectady the previous autumn. Langmuir attended the meeting, and while there renewed his acquaintance with a classmate of Columbia days, Dr. Colin G. Fink, who was then on the staff of the General Electric Research Laboratory in Schenectady. Industrial research was comparatively new in America; most scientists associated it with such pedestrian pursuits as tests and analyses; but as Dr. Fink conducted his friend through this laboratory, introduced him to members of the staff and to their work, the visitor was enormously impressed and interested. Here was an authentic atmosphere of research, and every facility to delight the heart of an experimenter. When, a few months later, the suggestion came that he spend his vacation in the laboratory at Schenectady, it was not difficult for Langmuir to accept.

2

Among the problems under scrutiny was one which we may call "the mystery of the lamp." The laboratory had been trying to improve the incandescent electric lamp, and had been blocked by a certain "offsetting" effect of the wire filament. Tungsten, which will endure more heat than any other solid, had been substituted for the earlier carbon and tantalum filaments, and the bulb had been exhausted of its air to an extent attained in no other laboratory; yet, after a few hundred hours of use, the tungsten became brittle, the filament crumbled, the lamp failed—and nobody knew why. Accidentally, three tung-

sten wires had been produced which gave fairly satisfactory results—but again, nobody knew why.

It occurred to Langmuir that there might be an impurity in the tungsten. Perhaps it had absorbed some gas, and possibly this foreign inclusion was responsible for its unaccountable behavior. As his summer's research Langmuir proposed to heat various samples of tungsten wire in high vacuum, and if any gases came off he would measure them. He set up his apparatus, obtained specimens of wire, installed one in a lamp, and attached a vacuum pump.

He got gas, plenty of it, and kept heating the wire and pumping the bulb until he had obtained an amount of gas equal to seven thousand times the volume of the filament. He was astonished. It was preposterous to assume that all this had been hidden within the hairlike strand of tungsten. Where did it come from? Langmuir spent all that summer trailing the gases to their sources, and never did get back to his original project of investigating the samples of wire. "How much more logical it would have been," he remarked later, in reminiscence, "if I had dropped the work as soon as it was evident that the method employed was not going to solve the problem of the brittleness of the wire."

Curiosity led him on. "Frankly, I was not so much interested in trying to improve the lamps as in finding out the scientific principles underlying these peculiar effects."

September arrived. The classroom in Hoboken was waiting, and here was its chemistry instructor in the midst of an engrossing experiment. The director of the laboratory, Dr. W. R. Whitney, asked if he would care to stay. Langmuir was eager to stay, but his Scotch conscience made him protest that he could not foresee any practical issue from his studies. "I am merely curious about the mysterious phenomena that occur in these lamps." The discerning Dr. Whitney recognized the temperament. "Go ahead; follow any line of inquiry you like; find out all you can of what goes on in a lamp."

And Langmuir did. The work absorbed him. He was given first one assistant, than others, and thousands of dollars were made available to provide the wherewithal for his flights into the vacuum. He continued to track down the ubiquitous gases to their lairs, and found that they came for the most part from the glass bulb. He continued to discover and record their varied behavior. He began to introduce other gases into the lamp, purposely to spoil the vacuum, to see what would happen. He worked in these ways nearly three years before any practical application was made of any of his results.

But in the course of these studies he became intimately acquainted with the invisible world of colliding molecules and curiously individualistic atoms. A trace of nitrogen introduced into the vacuum behaved very differently from its usual inert self. Pure oxygen had its own atomic antics. And so with each gas. Hydrogen was the most fascinating actor of all, and presently Langmuir was concentrating all his experiments on hydrogen. It lured him, as the North Pole had lured Peary, and nights and days he could think of nothing but the queer ways of hydrogen in a vacuum.

3

He found, for example, that the presence of any gas in the lamp accelerated the loss of heat from the incandescent filament. This was expected, for the gas molecules coming in contact with the hot wire take up some of its energy, which quickens their motion, and they fly off at higher velocities to bang into other molecules or against the inner surface of the bulb. Langmuir was familiar with this thermal conduction of gases. It was a subject he had studied at Göttingen under Nernst; he had worked out curves to picture the increase of conduction with temperature. But earlier experiments had been with filaments of platinum, which melts at 3200°F., and there were no data on performances at temperatures above 2000°F. Now he was working with the

most refractory of all the elements, tungsten, which must be heated to 6200°F. before it melts, and the experimenter was eager to see what would happen in the higher range thus opened up. He found that the ascending order of his curves continued with fair consistency for all gases—*except* hydrogen.

When hydrogen was introduced, and the electric current turned on, the rate of heat loss increased steadily until the glowing filament reached a temperature of 3600°F. Then the curve rose rapidly to a height five times as great as would be expected. Evidently, at these higher temperatures, something happened to hydrogen to make it a glutton for heat.

The hydrogen also staged a mysterious disappearing act. When a measured quantity of the gas was introduced into the lamp bulb, the pressure rose exactly as one would expect. But if you then turned the electric switch and lighted the lamp, the pressure slowly dropped to zero. The hydrogen had disappeared! More was introduced, and under like conditions it too disappeared, until finally a stage was reached when the pressure remained constant.

But where had the earlier hydrogen gone? The filament was suspect, but experiment soon exonerated it. The only hiding place left was the inner surface of the glass bulb. Langmuir put the lamp in an electric furnace and baked it, heated the thing until its glass was near melting. Then, at last, the lost hydrogen began to reappear. Like a swarm of leeches, its particles had attached themselves to the glass; and only the most drastic heat treatment could make them budge.

One more experiment, and the mystery was unmasked. Langmuir had introduced hydrogen into the bulb, had lighted the filament to incandescence, and the hydrogen had disappeared. His new experiment was to turn off the current, allow the filament to cool, and then to introduce a measured quantity of oxygen. Instantly the oxygen dis-

appeared. Other additions of oxygen vanished too, until a point of saturation was reached. It was noticed that the amount of oxygen taken up was exactly the quantity required by the hydrogen to combine in the proportions of H_2O.

Everyone knows that two parts of hydrogen join with one part of oxygen to form water, but only the chemist knows what tremendous activation is required to effect this union. You might mix the two gases till doomsday, and nothing would happen until you gave the mixture some violent molecular blow, as by an electric spark, a ray of ultra-light, or some other packed quantum of energy.

But here in Langmuir's experiment the union occurred spontaneously, in a cold lamp bulb, without any outside stimulus. Obviously the experience that had made the hydrogen such a glutton for heat, that had caused it to swarm to the inner surface of the glass, had also endowed it with extraordinary affinity for oxygen. It could no longer be regarded as the familiar hydrogen of ordinary usage, a gas which exists in compact molecules of two atoms each. It must be different. It *was* different. And now Langmuir knew precisely what it was, and saw how it came to be.

The tumultuous heat of incandescent tungsten had split the hydrogen molecule in two.

The bursting of these bonds had drained enormous energy from the tungsten, as was indicated by the extraordinary heat loss.

These sundered halves of the hydrogen molecule, these two separated hydrogen atoms, with their natural affinities now loose and unsatisfied, were eager for any kind of union —with oxygen, if oxygen was to be had; if not, with the glass surface of the bulb.

Theory had predicted that, if hydrogen existed free in its atomic form, it should have these characteristics. And now Langmuir had discovered it. The demon within the lamp was atomic hydrogen!

4

I have sketched this pioneer research in some detail, because it is one of the fundamental explorations of the new chemicophysics, now our basic science. Fifty years from now men will look back to it as to a lofty landmark in the march of discovery, just as today we rate Faraday's work with electromagnetism as epochal. Mr. Gladstone, attending an early demonstration of the dynamo, was prompted to ask Faraday, "But what use is it?"—a question which I believe Langmuir's discovery was never challenged to answer. No, the practical engineers at Schenectady knew what they were after all the time, and were wise enough to see that this quiet searcher in the laboratory, who was "merely curious about the mysterious phenomena that occur in these lamps," was getting somewhere—though they did not dream of the wealth of applications that would trail off from his indulgence of his scientific curiosity. Four practical results are outstanding:

1. First, better lamps. From his studies of the behavior of gases in the bulb, Langmuir learned that the vacuum was not the secret of lamp efficiency. The main effort of lamp makers up to this time had been concentrated on attaining higher vacua within the bulb, but Langmuir showed that the presence of gas was an advantage, provided it was the right sort of gas. For when the filament was coiled in a certain way and the bulb filled with the inert gas argon, the fatal crumbling away of the tungsten did not occur. The argon, by its gaseous pressure, prevented the filament from evaporating. By these and other innovations Langmuir halved the lamp's consumption of electric current. According to statisticians who keep tabs on such minutiae, this improvement is yielding the American public an average nightly saving of $1,000,000 on its electric-light bill.

2. His study of lamps led Langmuir to new methods of pumping vacua, and resulted in his invention of the

mercury condensation pump. By means of a blast of hot mercury vapor, this Langmuir pump siphons air out of a container so rapidly that in 5 seconds a quart bulb is emptied to a hundred millionth of an atmosphere. This means that in those 5 seconds the harnessed tornado of mercury jerks some 24,999,999 million million air molecules out of the bulb.

3. With this powerful pump Langmuir was able to attain degrees of emptiness far beyond any previously known, and these equipped him to penetrate still deeper into that world of the vacuum where radio communication has its home. He discovered the "space charge," now recognized as a fundamental principle of electronics. He found that an infinitesimal pinch of thorium added to the tungsten filament would speed up its flow of current a hundred thousand fold. By the summer of 1933, more than sixty patents had resulted from Langmuir's studies, about half his patents being in the field of radio engineering.

4. One of the more spectacular inventions in this list of patented results is the atomic hydrogen torch. The idea for this industrial application came as a hunch. Dr. Langmuir was with a laboratory colleague discussing some related matter, when suddenly it flashed in his mind that atomic hydrogen might be used to produce an intense flame. For, he reasoned, if the temperature of incandescent tungsten is required to tear the halves of the molecules apart, would not the broken molecules—*i.e.*, the separated atoms—if allowed to reunite, give up enormous heat in the process? The hunch was tried out, and it worked. Today the highest steady temperature that man has been able to generate and control is that of the atomic hydrogen torch. Above 6800°F. has been registered. The torch is used in welding the fine parts of machines and other metal constructions.

But these practicalities are only the fringes of his achievement. The really significant outcome that resulted

from the discovery of half a hydrogen molecule is its turning of attention to the chemical behavior of surfaces. The Swedish Academy of Sciences, in its citation, declares that the Nobel prize is awarded to Irving Langmuir "for pioneer work in surface chemistry." And here we are down to fundamentals. Surface chemistry represents a new and strategic attack on the hidden mechanism of nature.

5

Forty years ago Lord Rayleigh was enticed by the iridescent films which oil makes on water, and began important studies of these familiar phenomena. Our own Willard Gibbs interested himself in soap bubbles, was led to consider what soap does to the surface of water, and from these inquiries worked out a mathematical formula accounting for the surface tension of liquids. Later Sir James Dewar investigated the tendency of certain gases to attach themselves to the surfaces of charcoal—knowledge that was put to practical use during the World War in the manufacture of gas masks. Dr. Langmuir, in his pursuit of the energetic hydrogen in the lamp, found that the gas attached itself to the inner surface of the glass bulb in a *single* layer of atoms.

This discovery of the monatomic film was a revolutionary finding, though Langmuir was looking for just such an arrangement as the most logical outcome of his theory. Prior to this the generally accepted idea among chemists was that when atoms or molecules were *adsorbed*, or attached to a surface, the concentration was densest at the surface, and gradually thinned out with distance above the surface, like a miniature atmosphere. But here, in the case of hydrogen on glass, there was no hovering atmosphere—just one tightly held layer of atoms, and above that little attraction.

Langmuir explored other adsorbed films, and in every instance the film was one layer deep. In the case of carbon

monoxide (a compound of one carbon atom combined with one oxygen) the film was a single molecule thick—and here an interesting new detail showed itself: all the molecules attached themselves to the surface with the *carbon atoms down.* It was as though the carbon end were the head, and alone had the power to bite into and hold on to the surface.

Oil films on water showed the same orientation. The oil spread in a layer exactly one molecule thick, and each molecule clung to the water in a uniform way. These oil molecules are large. Predominantly they are groups of hydrogen and carbon atoms, some being chains of fifteen to twenty-nine of these groups linked together. All are alike in one peculiarity: they have at the end of the chain an atom of oxygen coupled with an atom of hydrogen. In every oil film of his experiments, Langmuir found, it was this OH end that attached the molecule to the water. It was the head. It was able to satisfy its own affinity for the water molecules, but was not strong enough to drag the long hydrocarbon chain down into the water.

In molecules of short structure it is able to do this; therefore such substances dissolve readily in water. Alcohol is an example. Its hydrocarbon chain is only two atoms long, and the eager oxygen-hydrogen head is able to pull the whole molecule under.

All the soluble carbohydrates are strong in the OH group. Sugar, for example, may be called hydra-headed, since in every molecule there are several OH groups—eleven in the familiar cane sugar that dissolves so readily in our coffee and tea.

In contrast with these mixers is a class of oils which will have nothing to do with water. Pure mineral oil is an example; it will neither dissolve nor form a monomolecular film. Examine the make-up of its molecule and you find it different from the others in one particular; it has no OH group. Bereft of a head, the molecules are neutral to surfaces, and so hold themselves apart in inhospitable globules.

These peculiarities of the infinitely little absorbed Langmuir. For months his laboratory was cluttered up with trays of water alive with invisible oil films. He began to measure the molecules. In the cases of stearic acid, a principal ingredient of candle tallow, he found that the length of the molecule is about one ten-millionth of an inch, its width about one-fifth as much. Other oils showed slenderer units. He visualized the oil film as made up of billions of long waving molecules, like eelgrass in a swamp, each a snakelike structure of linked atoms attached to the water by its active head.

As oil after oil was studied, various shapes showed up. The molecule of olive oil measured about the same in length as in thickness. A surface film of olive oil suggests more the appearance of a field of cabbages than of eelgrass. The castor-oil molecule showed an even more striking departure, for its height above the surface is only about a third of its diameter, giving the molecule the appearance of a disk. This is explained as an effect of its abundance of heads, for each molecule has not only three active OH groups at one end, but six additional ones on its sides; the affinity of the nine groups for water causes the molecule to lie flat rather than stand erect. As a result, the castor-oil film is exceedingly thin. It measures only one hundred-millionth of an inch.

6

These studies led Langmuir into a curious flatland. The adsorbed molecules could move about on the surface, but were unable to rise above or dive beneath it. Their actions constituted a chemistry confined to two dimensions. One day, in his laboratory, I watched him fill a tray with water and then touch the water surface with the tip of a needle that had been dipped in an oil (myristic acid). The oil instantly spread over the water as a film. Tests showed that its particles were in continual agitation, like the colliding

molecule of a gas. Indeed, the oil film was a two-dimensional gas which could move about freely in flatland, but apparently was unaware of the third dimension.

Langmuir demonstrated this. He laid a strip of paper across the water surface, and by gently pushing the strip forced the oil to one end of the tray. If the agitated particles had possessed any freedom to leave the surface, they surely would have used it to escape the crowding. Instead, under the pressure of the paper barrier which acted as a two-dimensional piston, the film condensed into a two-dimensional liquid. Further pressure converted this liquid film into a two-dimensional solid. The thin crust, measuring only one twenty-millionth of an inch in thickness, was invisible, but by blowing on it one could prove its rigidity. On the release of the barrier the pressure dropped, and instantly the two-dimensional solid melted into a two-dimensional liquid, which in turn evaporated into a two-dimensional gas and diffused over the surface as the freed molecules darted about, collided, and rebounded, in wild abandon. Why they had allowed themselves to be squeezed into solidity seems an amazing bit of chemical perversity—until one knows the eagerness of the molecular head for water. The OH group has an affinity.

This affinity is responsible for many characteristics of water itself. For not only does the OH head of the oil molecule have a liking for water, but the OH head of the water molecule has an enormous fondness for the oil. The three atoms of the water molecule H_2O are arranged in the sequence: H—O—H. Thus both ends of the water molecule are heads; on either side it presents an active group to its fellows. The mutual attraction of these molecular heads makes water molecules attract one another and gives to the liquid surface of water a strong "skin." It is this surface tension which enables insects to walk on water, causes particles of water to gang together into large drops, and endows the fluid with a high boiling point which distillers and other

commercial chemists find useful. These and other characteristics of water are accounted for by the predominating influence of the OH group.

To test this, destroy the OH group. It can be done by removing the oxygen atom from the water molecule. What is left is two hydrogen atoms, HH, which pair off as a single molecule of hydrogen. Normally the stuff is a gas, but by sufficiently lowering the temperature the gas can be reduced to liquid, and then liquid hydrogen may be compared, quality for quality, with liquid water. Striking results show up.

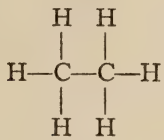
Hydrogen H—H	boils at 423° *below* zero F. has 5 units of surface energy occupies 47 units of volume
Water H—O—H	boils at 212° *above* zero F. has 118 units of surface energy occupies 30 units of volume

Note that hydrogen has very little surface energy. This means that its surface tension is slight; therefore it has a weak "skin." When liquid hydrogen is poured or spilled, it forms very minute drops. Attraction between its molecules is so feeble that at a temperature of 423°F. below zero, the molecules dart away from one another—*i.e.*, the hydrogen boils. This behavior is at the opposite extreme from that of water—and yet, the only fundamental difference between a hydrogen molecule and a water molecule is the absence of one oxygen from the hydrogen. By adding an O to the HH we make it possible for the molecule to develop an OH complex. The influence of that masterful combine gives the water molecule such compactness that its volume shrinks to about two thirds that of the hydrogen molecule. And it gives to all the water molecules such affinity for one another that the surface energy is increased above that of liquid hydrogen twenty-three-fold, and the boiling point is raised by 635 degrees.

This tenacity crops up all through nature. It explains many curious contrasts. For example, ethane, one of the

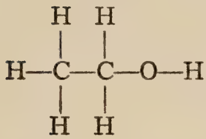
constituents of illuminating gas, differs in structure from alcohol by the trifle of a single atom. Ethane is C_2H_6, alcohol is C_2H_6O,—but what a difference in characteristics the presence or absence of that single oxygen makes!

Ethane



boils at 120° *below* zero F.

Alcohol



boils at 173° *above* zero F.

Ethane presents to the world an unbroken shell of hydrogen atoms, and it behaves much as hydrogen does. But add a single oxygen atom, and the upset is enormous. The effect is to break through the hydrogen and provide the molecule with an OH head. Ethane by this addition of oxygen is changed to alcohol, the boiling point is raised from minus 120°F. to plus 173°F.—and the tenacious OH group is the little giant that does it.

From such minute behavior Langmuir was led to formulate his Principle of Independent Surface Action, now recognized as a primary law of the new chemistry. It sees the compound molecule as a piece of architecture. Each group of atoms within the molecule has its individual surface characteristics. An OH surface is different from an H surface, just as a sun porch is different from a basement cell; and so with other groups. Dr. Langmuir found that he could predict molecular behavior by this principle. Also, by the same rule, from a study of behavior he could forecast structure.

Surface chemistry thus assumes a primary role in science. In the façades and other architectural peculiarities

of the invisible particles lies an explanation of the strange affinities and lack of affinities which bind and loose the physical world. Through knowledge of molecular surface differences has come increased ability to manage many phenomena to man's advantage. Not only better lamps, more sensitive radio tubes, and more absorbent gas masks, but also such varied practicalities as tough-skinned lubricants for airplane motors and other machines, improved flotation methods of extracting ores, the production of artificial fertilizers for agriculture, even a better understanding of the functioning of antitoxins and other serums in the human body, are derived from knowledge of this propensity of certain particles to arrange themselves on surfaces in single-layer films.

7

Soon after Langmuir published reports of his early discoveries in these chemical flatlands, he began to receive letters from cytologists, cancer specialists, and other medical researchers. They had been seeking to learn the "go" of the living cell, and were finding it increasingly a problem of surface behavior. At the thin wall which divides the living substance within from the multiplex world without, certain processes seem to act selectively. Just as the relations between oil and water are selective, binding some oils to water surfaces in a tenacious layer, and in other cases being so different as to drive the oil apart into unsocial droplets, so the interchanges between the internal protoplasm and the external nutrients and poisons seemed to suggest a monomolecular relationship. The biologists submitted some of their observations to the chemist for elucidation; and soon he was finding in their experiments new and tempting trails into surface chemistry. Could the curious actions of oil films throw a gleam on the mystery of life? He who in his youth had the longing to be "free to do research as I

wish" turned to that problem. He was not a biologist; he did not propose to dissect cells and test their behavior. But he was a chemist, and could go as far as he liked with his films, his interfaces, his two-dimensional gases, liquids, and solids.

The first account of the new studies in this biological direction was published in an address at Williams College in the autumn of 1936, when the hundredth anniversary of Mark Hopkins was celebrated there by a conference of scholars. Langmuir reported what happened to his oil films under changed conditions of acidity, alkalinity, and in the presence of certain familiar metallic salts. As the film material for these experiments he used a mixture of two fatty substances: the mineral oil petrolatum, and the tallow's stearic acid. The mineral oil has no OH group; therefore it has no molecular head to bite into the surface, and will not spread; it remains on the water as a bulging drop or spatter of isolated droplets. But the stearic acid has its OH group, and because of this active molecular head it quickly distributes itself over the water surface. When a small proportion of this gregarious stearic acid was mixed with the individualistic petrolatum, the mixture acquired an avidity for water and promptly spread into a surface film one molecule deep. The techniques of these experiments were developed by Katherine R. Blodgett, and also associated in the study was C. N. Moore; Dr. Langmuir reports the findings as the joint result of a collaboration between himself and these two associates of his laboratory.

As a starting point for the search, the investigators chose a water solution approximating that of sea water. Life thrives in the sea; evolutionists believe that it first appeared in the sea; in the animal body life requires a blood plasma of approximately the same slight alkalinity as sea water: therefore such a solution would appear to be normal to the living membrane of the cell. How would it affect the nonliving membrane of the oil film?

Well, when a drop of the oil mixture was placed on this slightly alkaline water (and the same proved true of pure water), the oil film quickly spread into a monomolecular film. And tests showed that the film was in the liquid state. That is to say, the oil molecules distributed themselves over the water surface with a density not so rigid as that of a solid and yet not so diffuse as that of a gas—they were a two-dimensional liquid.

When this water was made acid, marked changes occurred. Immediately the film expanded, the molecules moved farther away from one another, their agitation became greater—the two-dimensional liquid had evaporated into a two-dimensional gas. Further experiments showed that this response to changes in acidity and alkalinity was extremely sensitive. Even the slight acidity caused by the carbon dioxide of the air (which amounts to only a few hundredths of 1 per cent) transformed the oil film from the liquid to the gaseous state within a few minutes.

Then the experimenters tried a new tack. It is well known that salts of the alkali metals sodium and potassium are in solution in cell fluids and body plasma. Also those other kindred metals, calcium and magnesium, are in living tissues and fluids. How would these substances affect the nonliving film of oil? Very markedly, as the tests soon demonstrated. The addition to the water of a little soluble sodium salt or a slight pinch of potassium salt caused the film of two-dimensional liquid to change to a gaseous phase; the effect was similar to that of an acid. But calcium and magnesium operated quite differently; under the influence of salts of either of these metals the diffuse film of oil contracted, shrunk to a smaller area, and presently it had congealed into a two-dimensional solid. Thus the two pairs of metals have antagonistic effects. Calcium and magnesium cause the film to become more dense and less pervious; sodium and potassium open it up into a more diffuse and permeable structure.

These findings seem to have a bearing on the chemistry of life. Biologists long have known that the permeability of cell walls and other properties of cell material may be affected drastically by slight changes in the ratio of calcium and sodium salts dissolved in the surrounding medium. By changing the calcium content of the blood only a minute fraction it is possible to bring on biological disorders such as tetany. All activities of the living organism sift down at last to cell behavior; and if the interchanges by which a cell selectively absorbs nutrients from without and selectively discharges wastes from within are controlled by molecular forces at the cell wall, we have in these experiments with oil films a new and promising approach to fundamental problems of biology. In such studies we have an advantage over the usual techniques of the cell specialist with his microscope, for here we can observe the phenomena in the large. "We can make the artificial cell wall cover a square foot if desired," points out Dr. Langmuir, "and we can study in detail properties which would be very difficult to measure on a living cell. By quantitive studies we can derive fundamental laws that govern these changes in properties. We hope, by following up this work, we shall be able to establish some principles that will be of great use to the biologist in understanding the complicated dependence of living cells upon the composition of the surrounding medium."

But the structure of cell walls is more complex than any that can be represented by oil or other hydrocarbons. The molecules of the living membrane are larger, they have the added ingredient nitrogen combined with the familiar hydrogen, carbon, and oxygen, with occasional other elements, and these combinations assume enormous and complicated architectural forms which we call proteins. Some of the hydrocarbons contain scores of atoms to the molecule, but a protein molecule may contain thousands. For example, the stearic acid of our experiments is a

representative fatty substance; its molecule consists of 56 atoms. But the molecule of a representative protein, the familiar egg albumin, for example, consists of about 5000 atoms. And the latter complex substance is more typical of the cell material than are any of the oils, fats, or other hydrocarbons.

Langmuir and his associates have pushed their researches recently into the field of the proteins. In 1937 they announced some preliminary experiments with egg albumin. By a novel and original technique they have transferred monomolecular layers of these large particles to solid surfaces. And they have found it possible to alter the permeability and other properties of the protein films by making slight changes in the surrounding physical and chemical conditions—indeed simulating certain elementary biological behavior.

But there are larger molecular structures than those of egg albumin. The crystalline protein recently obtained by Wendell M. Stanley from the juices of diseased tobacco plants, and believed to be the virus of the tobacco mosaic disease, has molecules consisting of 2,000,000 atoms—perfectly gigantic structures, chemically speaking. Early in 1937 Dr. Stanley provided Dr. Langmuir with some of this virus protein, and it was found that when spread on water the virus formed a layer one molecule thick. The most amazing observation of these experiments, however, was the relative thinness of the layer. Although the virus molecule is atom for atom 400 times larger than the egg-albumin molecule, a layer of the virus on water is no thicker than that of the egg albumin. This may be explained, on the theory of Dorothy M. Wrinch, by assuming that the huge spherical molecule of the tobacco virus may unfold itself into a sheet which spreads out on the surface of the water. However, many biologists believe that the monomolecular films formed from these huge molecules may involve a breaking down of the molecular architecture from

complicated structures to smaller ones. Interesting tests of the film phenomena are continuing, exploring new bypaths.

The studies of protein films are highly significant. They advance the models of the chemist another step toward approximating the conditions of the biologist. In the protein experiments Langmuir has had the collaboration of Vincent J. Schaeffer; and in certain interpretations of their results they have been aided by Dr. Wrinch, biochemist of the Mathematical Institute at Oxford University. Does it not seem strange that an industrial research laboratory of an electrical manufactory should join forces with a mathematical institute to unshackle hidden meanings of life phenomena?

And so the busy vacation continues. Who could have foreseen in 1909 that the mystery of the lamp would shed light on the mystery of the living cell? that glowing tungsten could bring authentic clues of sensitive protoplasm? Surface chemistry is not only fundamental chemistry: it may be fundamental biology.

Chapter XI · LIFE AND THE QUANTUM

this tremendous scene,
This whole experiment in green.
—EMILY DICKINSON, XXXVIII

BIOLOGY is one of those intimate worlds which everyone claims as his parish. An American novelist describes the myriad reactions of consciousness as "chemisms." A philosopher and former premier of South Africa defines life "not as an entity, physical or other," but "a type of organization." Even in a book of astrophysics one may encounter biological dogma. "Man," ventures an astronomer of the Paris Observatory, "is only a colloidal oxynitrocarbide of hydrogen with some admixture, chemically speaking." Chemists are more analytical. They undertake to break down the admixture into its traces of metals and other infinitesimals, tab the results on a page, as one might write the recipe for a pudding, and announce that the chemical constituents are worth about 98 cents. Robots should be cheap—if we knew how to put the ingredients together.

Aye, there's the rub! We know fairly well of what the biological world is made, but we lack the fabricator's pattern. The blueprint of life remains to be discovered. Until it is found we may expect that such aberrations as cancer

and insanity will continue to pose their "infinite jests" on personality.

Protoplasm is both the nearest and the most remote aspect of nature—nearest because it is ourselves, the very stuff that breathes and thinks and inquires; and yet, to the investigator eager to unravel the secret of life, it sometimes seems more inaccessible than any star. There are stars that the eye cannot discern even through the 100-inch telescope, but the more sensitive spectroscope and photographic plate see and reveal them in such detail that it is possible to classify the stars precisely and form some definite picture of their inner structure. In certain fundamental aspects the astronomer knows the invisible star more exactly than the biologist knows the living cell.

But this comparison invokes the cosmic scale, and there stars are the norm and protoplasm the rare exception. More than 99 per cent of the visible matter of the Universe exists as stars and nebulae in a state of high temperature, incandescent, naked, completely gaseous, a comparatively simple and obvious system of atoms which is explainable in terms of physics and chemistry. A living cell, though almost inconceivably smaller, is far more complicated: a heterogeneous aggregate of liquids, gels, and gases, a comparatively chilly system which in spite of its low temperature is the seat of powerful molecular and atomic interactions that somehow spin their indefinable product, life.

Life comes only from life, in our experience. But life is also completely dependent on its nonliving surroundings; and by changing the physical or chemical environment life may be quickened and increased or retarded and destroyed —a fact which makes experimental physiology possible.

In 1912, at the Rockefeller Institute for Medical Research in New York, Alexis Carrel opened a hen's egg that was in process of hatching, removed the developing chick, and cut out a tiny fleck of its beating heart. This bit of

living tissue was transferred to a solution in a test tube. And there, protected from germs, poisons, heat, and cold, and provided with a never-failing supply of oxygen, sugar, and other nutrients, it lived and flourished as no heart cells in any living chick ever did. Indeed, it is doubtful if an animal could provide its tissue with such completely favorable surroundings; for in nature a heart as well as a chick must work for a living. Freed from workaday strains, the cells in the test tube proliferated so abundantly that it was necessary to prune down the tissue daily to hold the growth within bounds. Today, more than a quarter century since the beginning of the experiment, this part of the part of a chicken shows no signs of aging. On the contrary, there is reason to expect that it may continue to live a hundred years, a millenium, or until the Sun grows cold—so long as someone provides the necessary environment.

Dr. Carrel's experiment is a striking demonstration of the complete dependence of the living on the not-living—a commonplace observation, but its implications go to the root of our mystery. For when the chemist, sifting living matter into its elementary parts, discovers nothing new, nothing that is not already known in the rocks and the stars—

> Finding their mould the same, and aye the same,
> The atoms that we knew before—
> Of which ourselves are made—dust, and no more,

the question arises: At what point and by what means does inanimate matter pass over and become alive?

Outside the cell are compounds containing carbon, hydrogen, nitrogen, oxygen, calcium, sodium—all lifeless, familiar elements, common to earth, air, and sea, "dust, and no more." These diffuse through the cell wall and are converted into foods. The food products in turn pass over into new combinations and enter a new category. They become living matter: green chlorophyll, red hemoglobin,

protoplasm! Thus endlessly the line of life marches on, forever transporting star stuff into life stuff, moving by some catalytic hiddenness that is the very bridge of life.

To find that bridge has become the grand quest.

I

Among the agencies which the new physics has brought to the aid of biology in this search, none gives more promise of success than the quantum theory of light and the new implements and methods of generating, manipulating, and measuring radiation. Light, which opened to the astronomer the interior of stars and to the physicist the interior of atoms, is becoming the physiologist's surest instrument for exploring the delicate vital mechanism. Nor is it only an instrument; light is also one of the chief subjects of modern biological research.

For light is the great prime mover. Not long ago F. G. Donnan, chemist of the University of London, suggested a new holiday. He would have all city people make "a pilgrimage to the tilled fields and green pastures once a year, say when the first breath of returning spring brings its fragrance to our nostrils, or when the Sun rises on midsummer's morn, and, falling on the bosom of Mother Earth, offer thanksgiving for that bountiful conjunction of Sun and Earth, of radiation and matter, which sustains our life."

Such a festival might have a salutary effect on homocentric pretensions—reminding a proud race of its completely dependent position, not only in the cosmic scheme of things, but also among the living species. Whatever man may be mentally, physically he is a spender. He is as parasitic as any fungus, and in precisely the same way, *i.e.*, he derives his energy from the degradation of organic substances provided by other living beings. With the exception of a trifling fraction of power wrested from the harnessed

flow of water and wind, all the energy used by man—the fuel he burns in his furnaces and motors, and the food he burns in his body—is the product of a specialized type of plant cell which has the faculty of trapping and storing the energy of sunlight.

The importance of the plant's photosynthesis lies in this: that it acts *against* the energy stream. Man and all animals, the fungi and all parasitic plants, orchids and yeasts, move with the current. And that current forever flows downstream, from hot stars to cool planets and on to the absolute cold of interstellar space, ever falling to lower levels of energy, toward stagnation, equilibrium, maximum entropy, death. Against this universal waste the green plant sets a valiant barrier. It is not strange, therefore, that many biologists regard photosynthesis as the starting point for the grand quest. Some of the most penetrating research of modern biology has been in this field, and three of the recent Nobel prize men—Richard Willstätter, Otto Warburg, and Hans Fischer—are distinguished for studies of chlorophyll or its processes.

This enigmatic green stuff of plants—the trap that captures sunlight—is today the focus of experimental work in a score of laboratories, and an interest in hundreds of others. Present researches stem from the classic experiments of Willstätter, begun in 1902. It was in that year that the young German chemist—thirty years old—left Munich, where he had just worked out the difficult structure of cocaine and other alkaloids, to accept a professorship across the Swiss border in the University of Zurich. Here he tackled a more difficult structure.

"I remember well the time of my first experiments with chlorophyll," related Dr. Willstätter in a recent reminiscence. "I told my assistant to prepare a solution from grass under specified conditions. When he asked, 'Shall I order the grass from Mercks's?', I took him to the window and showed him the view from our old botanic garden. At our

feet lay a meadow, which perhaps was much greener than meadows appear to me nowadays."

But if Willstätter's studies took some of the greenness out of meadows—revealing that the chloroplasts always contain, in addition to their green pigments, smaller but quite definite proportions of yellow pigments—they also took some of the mystery out of the elusive sunlight trap. He broke it down into its molecular parts. He showed that chlorophyll is not one green substance, but two, each containing the familiar carbon, hydrogen, nitrogen, oxygen, and magnesium, but in slightly different arrangements. He traced the two chlorophylls to their chemical origins, and proved that the parent substance of the green stuff is closely akin to, if not identical with, the parent substance of the red blood pigment, hemoglobin. Thus, searching the secret of light's mechanism within the plant, the explorer comes upon a link with the animal kingdom. Hemoglobin is the carrier of oxygen within the animal body. Chlorophyll is the deoxidizer in the plant body. Their functions are basically different—yet blood and chlorophyll both own the same ancestry. The intrinsic unity of nature beckons to us from the most hidden places.

2

The key problem is to explain how the green pigment is able to bring together such mutually indifferent substances as water and carbon dioxide and, together with light, forge out of them a new compound, a substance of great energy content—sugar. For this is what photosynthesis does. Whatever may be the inner processes, we know what goes into the green cell and what comes out. The audit of the exchange balances precisely:

$$\underset{(6CO_2)}{\text{Carbon dioxide}} + \underset{(6H_2O)}{\text{water}} + \underset{(674\ \text{calories})}{\text{energy from Sun}} = \underset{(C_6H_{12}O_6)}{\text{sugar}} + \underset{(6O_2)}{\text{oxygen}}$$

The six parts of molecular oxygen produced are released and replenish the air. The one part of sugar is stored in the

plant for food. And, mind you, it is life's basic food. Out of it the cell builds the other carbohydrates, oils, and fats, and, together with combinations of nitrogen, fabricates the proteins. Sugar is the very fuel of life. It burns with oxygen like any other combustible, and its combustion yields back exactly the ingredients that went into its making: carbon dioxide, water, and the 674 calories of chemical energy. Any living being may set off this combustion process; indeed, it is continually occurring spontaneously. But only the might of chlorophyll can reverse the reaction and rebuild. And it must work with light.

Otto Warburg, at the biological laboratories of the Kaiser Wilhelm Institute near Berlin, tried the experiment of growing green algae under an illumination of weak light. The water plants developed dark cells rich in chlorophyll, and were powerful producers of sugar. It was found, however, that the average efficiency of the chlorophyll decreased as the intensity of the illumination was increased. The greater the input of light, the smaller was the output of sugar per unit of light, which seemed somewhat of a paradox until the discerning Warburg drew his picture of what was happening in the cell.

The chlorophyll molecules, being colored, are the absorbers of the light. It is known that this absorption can exist in each instance only a small portion of a second. Indeed, in most gaseous reactions, the period is limited to less than a millionth of a second. Therefore, whatever use is made of the energy must be within that slender whirl of time, and presumably it can be used only if the chlorophyll is in contact with a molecule or other unit of chlorophyll. As the process begins, this contact is 100 per cent; presumably every chlorophyll has at hand a carbon dioxide waiting to be reduced. As the intensity of the light is increased, the chlorophyll unit quickens the process; more and more sugar is manufactured; but presently the sugar is being produced faster than the cell transport can carry it away. The on-

coming carbon dioxide molecule now finds the assembly line blocked; it is unable to reach a chlorophyll machine; and so the works become clogged with their own overactivity—a demonstration from life of the evil of unbalanced production and consumption.

In offering this explanation Warburg was one of the first to apply the quantum theory to the photosynthetic process. According to this quantum theory, light is not emitted as a continuous flow of energy, like a stream of water from a nozzle, but in discontinuous units or quanta, like a stream of bullets from a machine gun. What the chlorophyll unit receives, therefore, is the blow from a bullet of energy shot out of some agitated atom of the Sun. The impact may be said to displace one of the revolving electrons within a chlorophyll molecule. In this process the energy of the quantum is absorbed by the displaced electron; but when the electron returns to its stable state in the molecule, the absorbed energy is released for use, again in the form of a quantum.

But all quanta are not the same. The energy varies with the wave length and frequency of vibration of the radiation. Blue light, being of shorter wave length and higher frequency than red, is packed with more energy. A quantum of blue gives the absorbing body almost double the kick that a quantum of red is able to deliver. And yet, chlorophyll does its most efficient manufacturing of sugar with red light, and actually uses mostly red light.

Seeking an explanation of this apparent contradiction, Warburg turned to the statistics of his experiments. He found that when photosynthesis was accomplished with blue light five quanta were necessary to reduce each molecule of carbon dioxide; but when the process was activated by red light, four quanta did the work. He was able to derive a mathematical relationship which showed why this must be so, namely, that four absorbed quanta were really involved in both cases, but in the first case one was wasted

in an incidental process. Another German biochemist, T. Schmucker, has since completed a series of experiments, using other methods, which confirm Warburg's results. The yellow pigments, although present to only one-fifth the extent of the green pigments, are very much stronger absorbers of blue light; and the quanta they absorb appear to be just so much wasted energy so far as photosynthesis is concerned, for the yellow pigments seem to play no productive part in the photosynthetic mechanism. It is the green pigment that does the work, and the green selectively absorbs red quanta to energize the photosynthetic unit.

But what is the photosynthetic unit? Is it a single molecule of chlorophyll, or many? Two American biophysicists, Robert Emerson at the California Institute of Technology and William Arnold, then at Harvard, worked on that question. They made use of a neon lamp which illuminates the green algae with very bright intermittent light, twelve flashes of light to the second, and each only one hundred thousandth of a second long. With this device they found that for every molecule of carbon dioxide reduced there were present in the cell an average of about 2500 molecules of chlorophyll. This does not mean necessarily that 2500 chlorophylls are active in the reduction of each carbon dioxide. Indeed, it is difficult to visualize so many large molecules (each containing at least 146 atoms) operating on one small carbon dioxide molecule of only 3 atoms. More plausible is the assumption that at each flash of the light many chlorophyll molecules are not functioning, and that the proportion of idle to active ones is roughly constant and tallies some 2500 for each manufacturing unit.

It may be that the unit is a supermolecule. Harold Mestre emphasizes in a recent paper that chlorophyll in the living cell is rather different from the extracted chlorophyll which we analyze in our test tubes. Absorption spectra and other indicators show considerable differences. Extracted chloro-

phyll has no power to make sugar. The meaning of the 2500 average is still under much investigation in an attempt to choose the correct interpretation from various ones proposed. The interpretation most favored at present involves a very great physical improbability, and while physiologists may accept it the physicists find difficulties which they are trying to obviate. It will be interesting to see which wins out, physiology or physics.

But the efficiency of photosynthesis in the living plant may be increased by artificial means. Warburg used intermittent light flashed from a rotating sector which divided each revolution into equal periods of light and dark. With this he found that when green algae were illuminated with 133 flashes per second, the rate of photosynthesis doubled per unit amount of light. More recently Emerson and Arnold used their flashing neon tube, adjusted to make the period of illumination only a small fraction of the dark period. With 50 flashes per second they were able to increase photosynthesis per light unit by as much as 400 per cent. Making five particles of sugar form where only one formed before is an achievement—and would seem to betray rather close contact with life's most fundamental process.

It is not a single process, but is now revealed as a cycle in which at least two operations continually follow each other. There is the *photosensitive phase*, actuated by visible light, completed in the hundred-thousandth part of a second. And there is a purely *chemical phase*, which is then completed in the dark, and takes at least a thousand times as long, *i.e.*, a hundredth of a second or more. This dark phase was predicted as long ago as 1905 by F. F. Blackman, a British botanist, and is known as the "Blackman reaction." The Emerson-Arnold experiments are convincing evidence of the reality of the Blackman reaction.

How then, after all, does the green-plant factory operate?

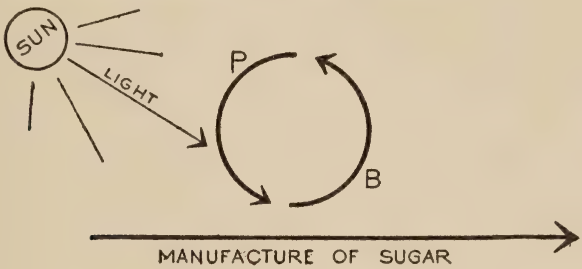
James Bryant Conant—who was working on this problem when Harvard University called him to its presidency—

suggested from his extensive chemical studies of chlorophyll that the sugar is made in the dark phase. He thinks this may be accomplished by a catalytic process of taking hydrogen atoms from chlorophyll and combining them with carbon dioxide in the pattern $C_6H_{12}O_6$, which is sugar. The reaction in the light follows instantly, according to Conant, and is a regenerative process to restore the sugar-making mechanism to its productive phase; it may do this by removing hydrogen atoms from water and using them to repair the mutilated chlorophyll molecules, at the same time setting the green stuff back to its former state packed with the energy of sunlight, primed and ready to repeat the cycle of manufacture.

Conant's theory is only one of many that have been proposed to explain photosynthesis; and like the others, it remains to be proved. All authorities are agreed that the photosynthetic process is cyclical, though the steps within the sequence may be far more complex than any present theory supposes. The Blackman reaction, for example, may be not a simple interchange but a train of two or more sequential operations. Recently Dean Burk and Hans Lineweaver, of the United States Department of Agriculture, proposed such a theory, whereby photosynthesis is analyzed into four forward reactions: *first*, a dark reaction which may take place in less than one-hundredth of a second; *next*, the photosensitive reaction which takes place in the light, and requires no more than one-hundred-thousandth of a second; and then *third* and *fourth*, two successive reactions in the dark, one building upon the other, these two constituting the phase known as the Blackman reaction, and together occupying about one-hundredth of a second. Burk and Lineweaver find that each of the four reactions is experimentally recognizable; each represents a step in the process by which sugar is made and the "machine" energized for the next reduction. The photosensitive reaction, which comes second in the sequence, appears in

some experiments to consist of several exceedingly rapid reactions. Thus the picture grows more complicated; the green-plant factory is no simple handicraft shop, but a highly specialized industrialism.

Whatever the internal processes and subdivisions of labor may be, we clearly distinguish the two phases, one using light and the other requiring no light, which constitute an unending cycle. Arnold has pictured the cycle in a simple graph, from which we adapt the following:



The arrow *B* on the right represents the Blackman (or dark) reaction or reactions; the arrow *P*, the photosensitive reaction or reactions; together they constitute a turning wheel driven by the energy of light. It is the rotating of this wheel, the two curved arrows following each other in perpetual sequence, that moves the process as a whole to manufacture sugar.

Whatever and wherever may be the bridge, surely here is the wheel of life—the whirling loom by which quanta are woven with atoms and molecules into the peculiar forms that nourish and make protoplasm.

3

But this universe of light contains more than visible radiation. As we noted in Chapter V, the rays we see are few and weak compared with the invisible light that is pouring through space—ultra-violet rays, x-rays, gamma

rays, cosmic rays, to name only the high frequencies. In addition to radiation, there continually move through the air and surrounding space countless ions or electrified particles similar to the alpha and beta particles from radium. These atomic particles dart in many directions at many velocities, some at speeds approaching that of light.

Now, it is in the midst of this fantastic turmoil, of bombardments and mutilations and rushings-about, that protoplasm has emerged and spread its film of life over the Earth. Did it do that in spite of the invisible radiations and collisions? or with their help? What happens when one of these projectiles smashes into a living cell?

Science has known for more than 30 years that radiation from radium and x-rays will destroy living tissue. Becquerel discovered this by chance when he carried a small quantity of radium in his coat pocket, and later suffered an ulcerating sore in the flesh under the pocket. This accident suggested the use of radium as a means of destroying cancerous tissue. Through the years the cancer specialists have accumulated considerable data on the biological effects of radiation. They found, for example, that young rapidly growing cells are more susceptible to its lethal action than are old cells. The tissues too show varying resistence. Blood, spleen, bone marrow, and other lymphoid cells are the most vulnerable, while nerve cells are the least. A body of empirical knowledge of this kind has been built up in the course of medical practice and is extremely valuable both to therapy and to experimental medicine. But the biophysicists aspire to apply exact quantitative methods to the phenomena, and lately some significant results have been obtained both in Europe and in the United States. A single series of experiments, conducted by Ralph W. G. Wyckoff at the Rockefeller Institute for Medical Research in New York, will serve to illustrate the procedure and its disclosures.

Dr. Wyckoff selected bacteria as the subjects for his studies. He proposed to bombard these minute creatures

with high-speed particles and rays of various frequencies, and measure the survival ratio. By applying the quantum theory to the results he was able to arrive at some picture of the changes brought about in living cells by these violent intrusions.

The first experiment—which was a joint project with T. M. Rivers—used a beam of electrons shot from a cathode-ray tube at a speed of 148,000 miles a second. An electron is an ion, the negatively charged fragment of a smashed atom; therefore these particles are comparable with the ions which eternally dart through the atmosphere. Known numbers of colon bacilli were spread in a single layer on an agar plate and bombarded with electrons. Out of every 1000 bacilli, 311 were alive at the end of 12 seconds, and only 26 at the end of 28 seconds. Similar experiments with other species of bacteria showed comparable results.

It is known that when an electron of this velocity is absorbed in matter, the effect is to release a large number of secondary ions within a very small space. The impact of the colliding particle sets off a veritable explosion, smashing out parts of atoms, each of which recoils at high velocity to wreak havoc wherever it strikes. Tests have shown that an electron of this velocity will liberate about 10,000 ions within a space of less than 1/1000 of a cubic millimeter—a space so small that about sixty such cubes would be required to cover the dot of ink which marks the end of this sentence. It is this sort of atomic pandemonium that is stirred up within the single cell of the bacterium. With thousands of its molecules thus dismembered and pounded into a frenzy of chaotic movements, the peculiar organization of protoplasm is destroyed. The experiment indicated two facts: (1) that a single electron hit can kill, and (2) that every absorbed electron is fatal to its living target.

For the second group of experiments Wyckoff used x-rays. Here the bombarding projectile is not a charged particle,

but something more penetrating—a quantum of radiation. Just as visible light has its range of energy proportionate to the frequency of its vibration, so with x-rays. The bacilli were bombarded with x-rays of five different frequencies, in progressive order of energy. This interesting relation was found: Millions of the rays passed through the bacteria without harm, other millions were absorbed without fatal effect, but when a death did occur it was the result of the absorption of a single quantum. Of the bombardment with the hardest or most energetic x-rays, about one bacterium out of every four that were hit, died; while of the bombardment with the softest rays, sixty were struck to one that died. (The criterion of bacterial death was the cessation of cell division; in the absence of simpler tests of life, Dr. Wyckoff assumed that when a bacterium ceased to multiply it had ceased to live.)

From the ratio of quantum absorptions to microbe deaths, considering also the frequencies of the rays and their ionizing powers, Wyckoff figured that the bacterium must be a differentiated structure in which there is a relatively small region sensitive to x-rays. It is as though a man were vulnerable to a bullet only in his heart, and if struck elsewhere would escape death. Wyckoff was able from his statistical picture to compute the probable size of this vital zone, and found that it measured about one one-hundredth the volume of the living creature. And the living creature, the colon bacillus, is a single-cell cylindrical rod measuring about 2/1000 millimeter long by 5/10,000 millimeter in diameter. Divide that by 100 and you have the size of the vital zone.

A third group of experiments used ultra-violet light. Although this is less energetic than x-rays, it carries more energy than visible rays. Using progressively five different wave lengths of ultra-violet, Wyckoff found that of the quanta absorbed by the microbes only about 1 in every 4,190,000 killed. Interpreted on the same basis as the x-ray

results, this would mean that the sensitive region of the organism is confined to the volume of a single large protein molecule—a conclusion which Wyckoff rejected as improbable. The fact that one bacterium can absorb millions of ultra-violet quanta without destruction, while another is killed by the absorption of a single quantum, is more reasonably explained on the assumption that some individuals among the bacteria are more susceptible than others to this form of radiation.

Several years before Wyckoff began these studies, H. J. Muller proved that it was possible to alter the inheritable characteristics of living creatures by x-ray bombardment. I have referred to these experiments in Chapter II, but the subject is vital to our present discussion and additional details will be interesting. Dr. Muller, a geneticist of the University of Texas, used the fruit fly (*Drosophila melanogaster*) as the material of his experiments. Selecting carefully nurtured strains of normal stock, Muller placed the flies in gelatin capsules, placed the capsules under x-rays of measured intensity, and after subjecting the flies to given periods of radiation, released them into larger bottles, where they were provided with food and all the other comforts of home. After several weeks had passed, and several generations had bred, the progeny of the x-rayed insects began to show strange deformities. Some of the offspring, for example, were born with huge wings, others with truncated wings, and many wingless. There were flies that grew extra antennae; in a few the antennae came large and thick; in one a leg grew out of its head in place of an antenna. Variations showed up also in the behavior of the insects. All these remarkable results are explained on the hypothesis that the genes, or units of heredity in the germ cells of the parent flies, had been struck by the x-rays or their ions and thereby had been twisted or sliced into new patterns. Comparing the slow rate of change in nature with the results obtained by a few minutes of intense x-radia-

tion, Muller reckoned that evolution had been speeded up 150-fold by the bombardment.

These experiments have led to speculations on the role of radiation as a factor in evolution. Mutations which produce new species of plants and animals may be accounted for as results of stray collisions of germ cells with rays or particles; though on statistical grounds it is argued that there are not enough of these strays observed in nature to account for the mutations that occur. Lately the geneticists have been looking within the living cell itself for the activating mechanism of mutation. It may be that chemical interchanges between the atoms and molecules of the genes, or of the substances surrounding the genes, cause the strange shiftings which later show up in the variants. It may be that molecular or atomic activity within the cell is able to produce an invisible radiation of its own, somewhat as the firefly and luminous bacteria emit their visible radiation. Life, whose wheel is driven by light, may also be a *generator* of light. This is the amazing concept posed by a series of experiments in a Russian laboratory.

4

The laboratory is the All-union Institute of Experimental Medicine at Moscow. Here for several years Alexander Gurwitsch has been at work with microscope studies of living tissue cells. These grow by a process of division, each cell reaching a stage when it splits and forms two cells, each of which in turn repeats the process. Watching this mysterious multiplication of life, Gurwitsch noticed that the cell division frequently followed a definite rhythm. For a year he concentrated on this study, and prepared a report summarizing his experiments. But the manuscript was lost in a censor's office in Leningrad, and most of these early data are unrecorded.

From the order of the rhythm Gurwitsch concluded that the cause must be physical. He suspected that it might originate in neighboring cells. One of the tissues that had

manifested the rhythmical division to a marked degree was the tip of an onion root, so this obliging vegetable was selected for the experiment. Several onion bulbs were allowed to sprout in water. After the roots had grown five or six inches long, the most symmetrical root was chosen and all the others on the bulb were cut away. This selected root Gurwitsch called the "sender." He proposed to use it as a biological cannon. He mounted it in a thin tube, setting it in a horizontal position that indeed suggested a miniature short-range artillery piece. He pointed the tip of this sender at another onion root, the "detector," which was similarly protected in a tube, but with a small area of its side exposed naked to the pointing tip of the artillery piece. The idea was to see if the growth of its exposed area would differ from the growth of other parts of the detector root.

After three hours' exposure to whatever influence the sender might have emitted, the detector root was sliced into sections suitable for examination under the microscope. And now, then, for the test! Gurwitsch counted the number of cell divisions on both sides, and found about one-fourth more in the exposed area than in an equal area on the opposite side. Apparently the biological gun had made a difference.

He tried the experiment all over again, this time interposing a thin sheet of quartz between sender and detector; the result was unchanged essentially. But when he repeated the experiment with a thin sheet of glass, or when the quartz was coated with a film of gelatine, the effect ceased. It is well known that quartz is transparent to ultra-violet rays, while glass and gelatin are opaque to them. From these and other considerations Gurwitsch concluded that the influence might be an ultra-violet radiation generated by the cells of the sender. Since it was the increased rate of "mitosis," or cell division, of the receiving root tissue that had betrayed the emissions, he named them mitogenetic rays.

Publication of these and later experiments evoked profound skepticism among biologists—and most of this attitude persists, especially in England and the United States. The wave lengths claimed for the mitogenetic rays are shorter, therefore more energetic and powerful, than the ultra-violet reaching us from the Sun, and it seemed incredible that living processes could generate such energetic quanta.

In Paris, though, J. and M. Magrou repeated Gurwitsch's experiments and reported similar results. Then T. Reiter and D. Gabor, in the research laboratory of Siemens & Halske Electric Company near Berlin, put the idea to the test in a series of experiments. Their verdict is that the rays are real. Others too reported confirmatory results, while a smaller number of equally reliable and conscientious investigators could detect no effects and were disposed to dismiss the whole idea as illusory.

Meanwhile, in the Moscow laboratory, Baron had found that yeast cells are sensitive to the radiation; and, because of the greater ease of handling, yeast took the place of the onion roots as detectors. The effect on yeast was to accelerate the rate of budding by a factor of 25 to 30 per cent. Later it was reported that bacterial growth was also stimulated by the mitogenetic effect, and cultures of these organisms have been used as detectors.

But biological growth is itself such an enigma that many authorities balk at the idea of accepting it as proof of an otherwise undetected radiation. Other causes might be influencing the growth. If the radiation really exists, argue these critics, it should be measurable on a physical basis like any other radiation. In accord with this idea, many attempts have been made to photograph mitogenetic rays, but always without success. It has been estimated that because the quanta emitted per second are so few relatively, an exposure of thousands of hours would be necessary to obtain appreciable blackening of the most sensitive plate.

This same limitation suggested that it might be impossible to measure the radiation by its ionization effect. But B. Rajewsky, working in Frankfurt, finally succeeded in installing an extremely sensitive photoelectric cell in an ionization chamber, and with this physicist's apparatus a purely physical detection of mitogenetic rays was reported. Other European investigators have confirmed Rajewsky's results; but a careful campaign of experiments made with a device of this same type was carried on in a Boston laboratory by Egon Lorenz of the United States Public Health Service, and his report is wholly negative. Lorenz was unable to detect any evidence of the radiation, though he tried seven different living tissues, all of which had been reported as good senders of mitogenetic rays. Even more recently another search was made in the United States, a study by Alexander Hollaender, conducted at the University of Wisconsin and supported by the National Research Council. Dr. Hollaender tried various methods of detection on several reputed senders, and his report may be succinctly summarized as: Looked for and not found. But as the great Warburg remarked recently, concerning these rays, "In science one cannot prove that there are no ghosts."

The negative results are extremely disconcerting to one on the side lines, however, especially in view of the wide range of living material for which other investigators have reported positive results. From the records of various successful experiments I glean the following items. Young cells radiate more strongly than old cells, root tips, dividing eggs, and other germ cells being particularly active sources. In mature animals, the working muscles, the cornea of the eye, blood, and nerves are energetic senders. Healing wounds give off rays, and it is claimed by some that the healing process is hastened by mitogenetic radiation. The blood of healthy rats gives off rays; the blood of starved rats does not; but when a little sugar is added to the latter, the radiation reappears. Illness seems to affect the quality

and degree of radiation, and the Cornell bacteriologist Otto Rahn reports that this has been observed of human senders as well as of lower organisms. Many simple chemical processes, such as the combustion in a gas flame, the digestion of proteins by pepsin, even the neutralization of acid by alkali, are reputed to give off characteristic radiations analagous to those of the mitogenetic effect.

Gurwitsch, on his part, is pushing the work into new fields. Dr. Hans Barth, a pupil of the late Professor Willi Wien of Munich University, has joined Gurwitsch's staff in Moscow, and Barth the physicist is attacking the mystery of the rays by purely physical means. Recently he reported the successful detection of the mitogenetic effect by a Geiger counter. The counter is an ionization device, an electronic apparatus that has been much used to explore cosmic rays. If other Geiger counters confirm Barth's report, the case for the elusive effect will be very much strengthened. A recent American visitor to the Russian laboratory found Gurwitsch completely convinced of the reality of his discovery, and equally confident as to the ultimate verdict of time.

Whatever that ultimate verdict may be, biological research will continue to explore its shadowy borderlands by the implements and methods and data of the radiologist. Radiation assuredly provides the energy to drive our wheel of life; demonstratedly it has provided a probe with which to reach into the living cell and alter and test the mechanisms of life; conceivably radiation is one of the products of life, certainly so in the case of the luminous organisms. Every year the techniques of the quantum physicists and the quantum chemists become more accurate, more sure, more penetrating, more available to the special needs of biology. The future of biology lies in increasing the approximate exactness of experiment. And an important sector of the future of biological experimentation, I venture to think, lies in the strange and mysterious ways of radiation.

Chapter XII · WHERE LIFE BEGINS

Self kindled every atom glows,
And hints the future which it owes.
—RALPH WALDO EMERSON, NATURE

OUR search for a bridge from the nonliving to the living leads eventually to a search for a definition. What does it mean to be alive? The physicist speaks of the "half-life" of radium as being 1600 years, somewhat as the biologist speaks of the average life of man as being about 60 years. The electrician warns us against the harnessed lightning bolt that is concealed in a "live" wire. The metallurgist describes the "growth" of crystals, the "fatigue" of metals, and the hysteresis or "memory" of certain materials, and some years ago the French scientist Dastre published a paper on "The Life of Matter." Indeed, life may be inherent in all matter, just as radioactivity and magnetism are.

It is in the massive chemical elements at the far end of the periodic table, vast bulky crowded atoms such as radium and thorium and uranium, that we observe radioactivity spontaneously occurring. But experiments early in 1934, in both Europe and America, have shown that light elements, even such gases as nitrogen, become radioactive under the battering of high-speed particles. Similarly, we

associate the property of magnetism with iron and nickel and cobalt and certain alloys of these metals; but the sensitive detectors of the modern magnetic laboratory reveal that all the elements possess a certain degree of magnetism. We can apply these facts by analogy to our discussion of life. Life is always associated with the element carbon, and the carbon seems to require as close collaborators the elements hydrogen, nitrogen, and oxygen. But may it not be that life, like magnetism and radioactivity, is a property latent in all atoms, a something hidden, waiting for a propitious meeting of matter with energy to bring it into play?

In truth, there is no *single* statement which the biologist asserts of the elementary behavior of the living species that cannot also be applied to nonliving matter. An organism reproduces itself, but so does a crystal of salt. A broken tadpole will grow a new tail, but so too will a mutilated atom repair itself. An amoeba responds to outside stimuli; it shows irritability—but an ionized gas molecule also responds to outside stimuli, to the electric or magnetic field, for instance. Both man and the paramecium breathe, but there are nonliving organizations also which take in oxygen and give off carbon dioxide. And, too, there are certain bacteria which live in the absence of oxygen and dispense with the function of respiration. There is no unique criterion of life, and no combination of tests which fits all cases. Perhaps, as a pragmatic device, in order to get on our way, we may adopt the subterfuge employed by the poet A. E. Housman when asked for a definition of poetry. Housman, as he relates the incident in a lecture, told his inquisitor that one "could no more define poetry than a terrier can define a rat, but that I thought we both recognized the object by the sympathy which it provokes in us."

All authorities, from terriers up, probably agree that the rat is alive. Cut off the rat's legs, and the mutilated animal will live. We can break down the whole yet more drastically, remove its heart, suspend that organ in a perfusion ap-

paratus, and keep the part of the rat alive for months, perhaps indefinitely. It is not necessary to remove the organ whole. We may cut a small piece out of the heart, and by immersing it in a nutrient solution and providing conditions favorable to its welfare, demonstrate that the excised tissue will live separated from its whole.

Under the microscope we see that the tissue is made up of individual units, minute blobs of jellylike fluid held within delicate membranous walls. Each of these cells is alive, and it is reasonable to believe that each could be cultured in a glass vessel if our techniques were sufficiently delicate to care for an object so small. Indeed, we know that cells live independently, for there are numerous species of one-cell plants and animals which carry on within their single room all the vital functions—and tissue cells are simply specialized individuals of the same general nature.

We may assert quite definitely, therefore, that life, this thing of wholes, can be broken into organs, and the separate organs will live. The organs may be cut into tissues, and the excised tissues will live. The tissues may be divided into cells, and the individual cells will live.

Is this the limit? Is it impossible for part of a cell to carry on? Or can we dissect still more, break the cellular whole and find some part that is more alive than the other parts, some smaller unit which is the kindling spark of this mysterious flame—the place where life begins?

It is a remote frontier that this question refers us to, but a fascinating one. I shall attempt in this chapter to give a brief account of several current discoveries which seem to bear on the question, and of certain speculations which have been ventured in interpretation.

I

Watch almost any living cell under a high-power microscope. You look in on a world of ceaseless change. Within the delicate membrane of the cell wall, the protoplasm

churns and flows. Perpetually the living stuff is on the move, and yet it maintains from moment to moment a certain differentiation in which we may identify relatively stable parts of the cell. Central, or nearly central, in this dynamic structure is a region, generally spherical or oval in shape, that appears more dense than its surrounding medium. This interior protoplasm is the "cell nucleus," and the surrounding thinner fluid is the "cytoplasm." All types of cells but a very few, like bacteria and some algae and blood corpuscles, have an easily recognizable nucleus.

It is possible to puncture the cell wall without killing the cell. It is possible to remove much of the cytoplasm without killing the cell. Indeed, the loss will be made good by the manufacture of new cytoplasm. The cell, like the tadpole, is capable of a limited regeneration. But if you injure the nucleus, the case is quite different. That inner zone is vulnerable. It cannot long survive the removal of any part of its substance.

The crucial role of the nucleus may be demonstrated in another way if we select for experiment those peculiarly endowed units of protoplasm known as germ cells. These, the egg cell of the female and the sperm cell of the male, have through the evolutionary ages become specialized as carriers of life. Some years ago it was discovered that by treating the egg (that of a sea urchin, for example) with a salt solution, or by pricking it with a needle, or by other mechanical means, the cell could be artificially stimulated to develop and produce a new sea urchin. You might cut the egg in two, leaving the nucleus in one half. The half containing the nucleus could be fertilized, but the other half was sterile. In the case of some animals, in which the nucleus is a very small part of the egg, the removal of the nucleus left the egg nearly entire; but an egg so mutilated had no power of reproduction.

Normally, in nature, fertilization is accomplished through penetration of the egg by the sperm, which makes contact

with the nucleus and merges with it. The sperm cell is extremely small. It may bulk only a few hundredths the size of the egg. It consists of a bulbous nuclear head and a short thin trailing thread of cytoplasm. But small as it is, the sperm cell carries all the pattern of characteristics of the father which are to be inherited by the child. Might it not also carry the spark of life to one of those bereft eggs of our experiment—the ovum from which the nucleus has been removed? This was tried, and it worked. When an egg fragment consisting only of cytoplasm was exposed to a sperm cell of its species, the sperm entered the fragment and by this merger supplied the necessary nuclear material—for thereafter the fragment quickened, began to divide, and grew into a new individual.

It is the nucleus, then, that is the captain of life. How potent it is, how packed its small volume, is graphically suggested by H. J. Muller in his book *Out of the Night*. Dr. Muller computes that if all the human sperm cells which are to be responsible for the next generation of the human species, some 2000 million individuals, could be gathered together in one place, they would occupy space equivalent to that of half an aspirin tablet. The corresponding number of egg cells, because of their larger component of cytoplasm, would fill a 2-gallon pitcher. But since it is the nucleus that carries the stuff of life, we may consider only the nuclei of these eggs and reckon that they would occupy no more space than the sperm cells. Thus, the essential substance of both eggs and sperm could be contained in a capsule the size of an aspirin tablet.

It is indeed difficult to believe, as Dr. Muller points out, "that in this amount of physical space there now actually lie all the inheritable structures for determining and for causing the production of all the multitudinous characteristics of each individual person of the whole future world population. Only, of course, this mass of leaven today is scattered over the face of the Earth in several billion sepa-

rate bits. Surely, then, this cell substance is incomparably more intricate, as well as more portentous, than anything else on Earth."

Some of its intricacy can be made visible under a microscope, by using suitable stains. Then we see the organs of the nucleus, the minute sausage-shaped "chromosomes." It is not only in the germ cells, but also in the somatic or body cells, that the chromosomes are found, the structural pattern being repeated in every cell. And the pattern is specific. Every species of plant and animal has its typical number of these nuclear organs, and for each there is a standard shape, size, and arrangement. The cells of corn have twenty chromosomes; those of the lily, twenty-four; of the frog, twenty-six; of man, forty-eight; of the horse, sixty. I have been curious to know the chromosomal equipment of the elephant and the whale, but can find no record that anyone has ever investigated the minute structure of these largest of the beasts. The monkeys of Asia and Africa have exactly the same numerical endowment as man, forty-eight chromosomes; but the South American monkeys apparently are more distant in their relationship with fifty-four.

One of the most productive researches of the twentieth century is the tracking down of the relationship which these microscopic nuclear bodies bear to the factor of heredity. The studies were focused on fruit flies. Thomas Hunt Morgan and his associates, working at Columbia University, cultured the tiny insects (*Drosophila melanogaster*) in bottles, provided the optimum of conditions for their growth and reproduction, and kept exact pedigrees through many generations. As new flies hatched out, the biologists examined the young individuals for possible changes in physical character. It was not long before they were finding changes.

For example: the bulging eyes of drosophila are normally red, but occasionally a white-eyed child would hatch out.

Morgan and his men were able to correlate this mutation with a change in a certain region of one of the chromosomes of the egg which gave birth to the fly. Later they found nine variations in the wings, and following that came discovery of scores of variations affecting practically every visible characteristic of the fly—physical changes which the investigators were able to relate to changes in the chromosomes.

These studies were reinforced by the radiation technique first successfully used by Dr. Muller. Through his bombardment of flies with x-rays, Muller showed that the rate of mutation could be increased many times that spontaneously occurring in nature. This confirmed the direct relationship between definite areas of the chromosomes and physical characteristics of the flies born of the chromosomes. The crash of the rays into the minute cellular organs was both destructive and constructive. In some cases part of a chromosome was blasted out, to disappear. In some, the fragment attached itself to the end of another chromosome, thus forming a new structure of unusual size and shape. In other experiments, chromosomes were sliced in two, and the half of one was exchanged for the half of another to form new combinations. All these chance alterations of the nuclear structures showed up in physical changes in the offspring of the bombarded flies.

By these and other experiments a new credence was given to an idea that had long been held as an inference. They indicate that the chromosomes are not simple continuous wholes, but are complex patterns made of smaller interchangeable units. And these units are the "genes."

No one has ever seen a gene. It is too fine for even the ultramicroscope to enlarge to visibility. But just as we postulate invisible atoms to account for the chemical and optical behavior of matter, so we find it necessary to postulate invisible genes to account for the developmental behavior of protoplasm. Genes are the unit structures, the atoms of heredity.

Nor is that all. Recent findings bring evidence of a still more fundamental role. Experiments show that the injury of genes may be a very serious event in the history of a cell. The loss of certain genes means death. And this suggests that the gene's function in the cell activities is not merely to control heredity, but also to control life.

2

Discovery of the primary vital role of the genetic unit is the work of M. Demerec, a geneticist of the Carnegie Institution of Washington, member of its Department of Genetics at Cold Spring Harbor, Long Island. For some years Dr. Demerec has been watching the effect of mutations on the reproductive capacity of drosophila. He was impressed by some experiments completed five years ago by J. T. Patterson at the University of Texas. Dr. Patterson found that out of fifty-nine mutations in three well-defined chromosomal regions, fifty-one were what he called "lethals." That is to say, when a fertilized egg carried these changed chromosomes (in which certain genes were missing), the egg developed only part way and died as an embryo. The gene deficiencies were fatal to development, therefore lethal to the fly.

Demerec followed this pioneer work with an intensive search into the somatic or body cells of the flies. He found that not only were the germ cells rendered incapable of development, as Patterson's results showed, but the growing body cells, which by a special treatment had been made deficient in these same ways, were rendered powerless to grow. And the cells died—though adjacent body cells, which carried no deficiencies, showed no such effects. Demerec's later work has demonstrated that more than half of Patterson's lethals are cell lethals. And by further extension of experiment and inference the Carnegie biologist arrives at the conclusion that some of these cell lethals

are chargeable to the loss of a very few genes, possibly only *one* gene.

How large is this genetic unit? No one knows, and apparently the only present way of approaching the problem is to find out how many genes there are in the chromosomes, divide the total length of chromosomal material by the number of genes, and so arrive at an average value.

The number of genes may be assumed to correspond to the number of places in the chromosomes at which changes occur. By mathematical analysis of mutations it has been figured that in drosophila there are about 3000 such places, which means that each cell has at least 3000 genes.

Quite recently a new and more direct method of determining the number of genes has been introduced through the work of Theophilus S. Painter, at the University of Texas. The larva of the fruit fly, like man and other animals, has salivary glands situated near its mouth, and in flies these glands are made of giant cells. The cells are many times larger than the other body cells, and the chromosomes are about 150 times the size of the chromosomes of the germ cells. This fact has been known for several decades, but apparently no geneticist thought to search the chromosomes of these giant cells for fine-structure details of mutations until Dr. Painter took up the work in 1932. He found that under a certain technique of staining and illumination, the giant chromosomes revealed themselves as chainlike structures of varying width made up of transverse bands of different sizes, each band showing a highly individual pattern of yet finer parts. The band is not the gene—no geneticist claims that—but it appears to be individual to the gene, each is the holder of a gene, "the house in which the gene lives," to quote Painter's picturesque phrase. Therefore, by counting the number of bands, we should arrive at the number of genes.

Here we are attempting to separate structures so fine that they approach the limit of visibility under the most

powerful magnification. Early counts showed about 2700 bands distinguishable, but recently Calvin B. Bridges, using a more delicate technique, counted 5000 bands. There may be more, and with further advances in microscopy we may some day be able to see them one by one. Painter has suggested a total of 10,000 as a guess. And some late speculations of Muller open up the possibility of an even larger total.

But, in order to be very conservative, suppose we take Bridges' count as our basis. If there are approximately 5000 genes to the drosophila cell, then we may say that one gene is not more than the five-thousandth part of the chromosomal material. But the chromosomes, in turn, are probably not more than a hundred-thousandth part of the average cell. The gene then figures roughly as not more than one five-hundred-millionth of the total cell material. We arrive at a picture of a mechanism so delicately balanced, and of a unit so indispensable to the smooth running of this mechanism, that although the unit represents only the five-hundred-millionth part of the whole, its elimination is fatal.

What is the nature of this indispensable unit of life?

A novel answer to that question was recently proposed by Dorothy M. Wrinch. Dr. Wrinch sees the chromosomes as made up of numerous filaments of protein molecules linked end to end and bound together into long bundles by a cross weaving of ringlike molecules of nucleic acid. On this view, a gene is regarded not so much as a discrete particle, as simply a peculiarity in the chromosomal structure arising out of the diverse overlapping and interweaving of the two kinds of molecules, the warp and woof of this protoplasmic texture.

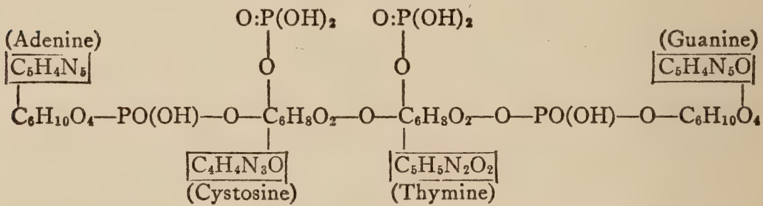
The view more generally held among geneticists favors the particle idea, however. Dr. Demerec pictures the gene as an organic particle, and suggests that it may be a single large molecule. The observed instability of certain genes seems evidence for this conception. Thus, it has been noticed

that the genic pattern responsible for wing formation, which normally endows a fly with long wings, will sometimes change to a form producing short miniature wings, and later shift back to the long-wing structure. These alterations may be accounted for if we assume the gene to be a large molecule which suddenly loses one of its subgroups of atoms, and later recaptures and recombines the separated parts. Other evidence adduced from the study of unstable genes indicates that when a cell divides to form two cells, the genes do not divide, but each is exactly duplicated by the formation of a new gene next to the old one. This method of reproduction favors the supposition that the gene is a single molecule.

If it is a single molecule, it must be a large one. Organic molecules of extremely complex structure are known to chemists. Some proteins consist of thousands of atoms. But these are too complicated, their structures too labyrinthine, to attempt to represent them here. As suggestive of the plan of a large organic molecule such as we may suppose the gene to be, Demerec cited a comparatively small molecule—a structure compact enough to lend itself to diagramming within the width of an ordinary book page, and yet sufficiently complex to illustrate the principle—the compound known as thymo-nucleic acid. It is one of the products that we get from the chemical breakdown of nuclear protein.

A molecule of thymo-nucleic acid consists of 59 atoms of hydrogen, 43 of carbon, 32 of oxygen, 15 of nitrogen, and 4 of phosphorus—a total of 153 atoms, with a molecular weight of 1421 (in terms of hydrogen as 1). The arrangement of these atoms conforms to a certain architectural pattern. A house of 153 rooms might be analyzable into a central structure with attached wings and towers—and similarly we find the 153 atoms of this molecule organized in a fixed sequence, with subgroupings and linkages, following the arrangement mapped on page 226.

The map outlines a central structure flanked by four smaller simpler structures. Each of these four subordinate parts may also exist separately. There is a compound of carbon, hydrogen, and nitrogen which the organic chemist knows as "adenine," and so too there are "cystosine," "thymine," and "guanine." One may imagine a thymo-nucleic acid molecule in which the bond attaching an oxygen atom of the thymine group is very weak. There might be a tendency for this oxygen to break off. Such behavior would be analogous to that of an unstable gene, in which a sudden change occurs and causes a mutation.



Map of a Molecule of Thymo-nucleic Acid

But conceivably some losses may be so serious as to interfere with the functioning of the molecule. For example, the thymo-nucleic acid has 32 atoms of oxygen but only 4 of phosphorus. If something should happen to dislodge or cripple one of the oxygen atoms, the loss would be only a thirty-second part of the oxygen equipment and might possibly be endured or repaired from the environment. But the elimination of one phosphorus atom would be more drastic: it would deprive the molecule of a fourth of its phosphorus mechanism, and the loss might be irreparable.

This latter example suggests what may happen to a gene in those mutations called lethal. The elimination of a single atom may so change the gene structure that its duplication is rendered impossible. And when gene duplication stops, cell division in many instances is blocked.

Thus we are led to a view of the protoplasmic world in which a single small unit becomes critically important.

Deprived of this small unit the gene cannot function; deprived of the gene the chromosomes cannot function; and with the paralysis of the chromosomes the functioning of the cell is halted. Cell growth stops, reproduction ceases, life comes to an end. If life comes to an end with the failure of a gene, may we not infer that life begins with the functioning of the gene?

Of that functioning we know only three results surely: (1) that in the process the gene is exactly duplicated, (2) that the gene occasionally mutates, (3) that genes somehow control and pass on to the developing organism the physical characteristics which distinguish it. But all these operations are manifest only in groups of genes. Indeed, we know genes only as they function in the closely related teamwork of the chromosomes. But suppose a gene should get separated from its fellows. Imagine one of these living molecules adrift in the cell fluid, or a wanderer in the body plasma. Could it function independently? If so, with what effect?

Several years ago B. M. Duggar, of the University of Wisconsin, speculated on this possibility. Dr. Duggar suggested that a lone gene might be a destructive agent. He pointed to the filtrable virus. Might not the virus be simply a gene on the loose?

3

The virus has been known for more than 40 years. It has long been a candidate for recognition as the most elementary living thing, and Duggar's suggestion offers presumptive argument for such rating. But first let us review what is known of the virus. Recent research can help us, for within the last 2 years an exciting discovery has been made. Wendell M. Stanley is the discoverer.

Dr. Stanley is an organic chemist. A graduate of Earlham College, he spent postgraduate years at the University of Illinois working on leprosidal compounds, then studied in

Germany on a fellowship from the National Research Council, and in 1931 joined the staff of the Rockefeller Institute for Medical Research in New York. In 1932 the Institute opened additional laboratories near Princeton, and Stanley went there with definite designs on the virus.

The nature of the virus is one of the key problems of pathology. Such destructive diseases as infantile paralysis, influenza, parrot fever, rabies, "St. Louis" encephalitis or sleeping sickness, yellow fever, and certain types of tumorous growths are propagated by these invisible carriers; therefore virus investigation is a major project for medical research. Pathologists and other biologists have specialized on biological aspects, and have turned up many important facts about the physiological effects of the virus and its response to various agents. Stanley the chemist was asked to specialize on chemical aspects—to find out, if he could, what a virus is in terms of molecules, and what the molecules are in terms of atoms: how large, how massive, how composed, how reactive?

He chose for his inquiry the oldest known virus, that which causes the tobacco mosaic disease. This is a pestilence dreaded by tobacco growers, for if one plant in a field contracts the disease, the infection usually spreads through the entire acreage, stunting the plants, puckering their foliage, and causing the leaves to assume the mottled appearance of a mosaic. Back in 1857, when mosaic disease was first recognized, it was confused with a plant pock affliction, and not until 1892 did the botanists realize that the two diseases are different. This discovery was made by the Russian investigator Iwanowski, and he startled the bacteriologists of his day by announcing that the juice of infected tobacco-mosaic plants remained infectious after it had passed through a Chamberland filter.

Now a Chamberland filter is a porcelain affair with pores so fine that if a pint of distilled water is placed in the filter, many days will elapse before the liquid percolates through,

unless strong suction is applied. There was no known bacterium that could get through such minute holes. And yet, the agent which communicated the tobacco mosaic disease readily passed. Other experimenters confirmed Iwanowski's findings, and six years later the first filtrable carriers of an animal contagion were discovered in the foot-and-mouth disease. Since then scores of afflictions affecting plants, animals, and man have been identified as virus infections. Of all the viruses, tobacco mosaic virus is conspicuous in its possession of properties which enable it to be worked with easily. Furthermore, it has long been regarded as typical and representative.

On the acres near Princeton, Stanley grew thousands of tobacco plants, infected them with the disease, later ground up the dwarfed, puckering, mottle-leafed plants, pressed them to a pulp, and collected the juices. Somewhere in the gallons was the virus. You could not see it, you could not accumulate it in a filter, you could not culture it in agar or in any of the soups used to grow bacteria. You knew it was there only by its destructive effect. For if you took a drop of the juice and touched it to a healthy plant, within a few days the leaves showed the unmistakable signs of mosaic. The virus was there. But how to get at it chemically?

The known ingredients of protoplasm may be grouped in five classes: metal salts, carbohydrates, hydrocarbons, lipoids or fatty compounds, and proteins—these last the most complex of all. There are certain enzymes which break up proteins. Protein splitters, or protein digesters, they are called. Pepsin, for example, does precisely that in the stomach, and will do the same in a test tube. What would it do to the virus?

Stanley put some of the infectious tobacco juice in a test tube, poured in pepsin, kept the mixture at the temperature and in the other conditions favorable for pepsin digestion, and at the end of the experiment tested the solution for infection. It had none. Rubbed on the leaves of healthy

tobacco plants it showed no power to transmit the disease. Obviously the pepsin had destroyed the infectious principle in the juice. But pepsin digests only proteins—it has no effect on lipoids, hydrocarbons, carbohydrates, and salts. From this it seemed reasonable to conclude that the virus material is protein.

There are chemicals which precipitate proteins. These were tried on the virulent tobacco juice. Immediately certain substances dropped down as solid precipitates, and it was found that thereafter the juice had no power to infect. But when some of the precipitate was added to neutral liquid, the solution immediately became infectious. This plainly said that the disease carrier resided in the protein precipitate, and Stanley now began a campaign to trace the carrier down to its source.

He dissolved the precipitate in a neutral liquid, and added an ammonium compound which has the faculty of edging protein out of solution without changing the protein. A cluster of crystals began to form at the bottom of the test tube—somewhat as sugar crystals form in syrup. But these might not be a single pure stuff, so Stanley sought to refine them. He removed the crystals, dissolved them in a much larger volume of neutral liquid, and with the help again of the ammonium compound brought this more dilute solution to crystallization. His next step repeated the process, but with still greater proportion of the liquid. In this way, by increasing the dilution each time, the chemist carried his material through ten successive fractionations and recrystallizations. One would assume that by now the substance was pure, that all extraneous materials had been separated out, also that all living matter had been eliminated—for we know no plant or animal, no bacterium, no protoplasm, that can undergo crystallization and remain the same. So the experiment seemed ripe for a supreme test.

Stanley took a pinch of the product of that tenth recrystallization, dissolved it in a neutral fluid more than 100

million times its bulk, rubbed a drop of the solution on the leaves of a healthy tobacco plant, and awaited the result. The test was conclusive. Within the usual time the plant showed all signs of an acute outbreak of the mosaic disease. Surely in the crystals we have the virus. And since, by all rules of chemistry, the crystals have been refined to the pure state and may be accepted as an uncontaminated single substance, it seems reasonable to believe that *the crystals are the virus.*

I have watched them through the microscope: a mass of white needlelike structures bristling in every direction. It is not supposed that each needle is a virus. Just as each crystal of sugar is made of numerous molecules of sugar, so it is presumed that each of these crystalline spikes is a cluster of millions of molecules of the protein, and that *each molecule is a single virus.*

Stanley's chemical analysis shows that the virus molecule is composed of carbon, hydrogen, nitrogen, and oxygen. Unlike many other physiologically active proteins, it contains no sulphur and no phosphorus. Just how many atoms of each element are present, and the arrangement of the atoms in molecular architecture, are details still in process of investigation. But the evidence indicates that the molecules are enormous.

Ingenious physical measurements of the molecules were recently made by The Svedberg, at the University of Upsala, and by Ralph W. G. Wyckoff, at the Rockefeller Institute, using centrifuges of the ultra type. The apparatus is a whirling machine capable of doing better than 100,000 revolutions per minute. Dr. Svedberg's apparatus is made of steel, and is driven by a stream of oil pumped at high pressure. Dr. Wyckoff's apparatus is made of an aluminum alloy, and its turbine is driven by compressed air. In both machines, the rotating part is housed in a chamber made of 3-inch armor-plate steel—a safeguard to protect the operator in case of explosion. If a dime is placed in the

ultracentrifuge, and the apparatus is rotated at a certain velocity, the centrifugal force is so great that the dime presses out with an effect equal to the weight of half a ton. The purpose, however, is not to perform trick stunts with dimes, but to separate mixtures of molecules, using a principle long familiar in the dairyman's cream separator. In the ultracentrifuge this principle is harnessed to the utmost degree of control. Under the accelerated fling of centrifugal force generated by the rotating mechanism, molecules in solution are separated, each is thrown out with a speed proportional to its mass, and by timing the period required for its separation the molecular weight and size of any constituent may be determined. Dr. Stanley sent Professor Svedberg samples of his crystals, and at the same time supplied specimens to his colleague Dr. Wyckoff, and to the test of this indirect weighing and measuring machine the substance was subjected.

The results are in remarkable agreement. Both Svedberg and Wyckoff independently reported that the weight of Stanley's crystalline protein is approximately 17,000,000 (in terms of hydrogen's atomic weight of 1). The largest molecule known up to this time was that of the animal protein called hemocyanin (which is the pigment of earthworm blood), with a molecular weight of about 5,000,000. Thus Stanley's find is more than three times heavier. In size it appears to be egg-shaped with a diameter of about 35 millimicrons. The corresponding dimension of the hemocyanin is 24 millimicrons. And a millimicron is 1/25,400,000 inch.

The tobacco mosaic protein thus provides the chemists, the molecular architects, the microcosmic adventurers, with a perfectly enormous molecule for their exploration: a structure many times more massive and complex than anything heretofore analyzed. It must consist of hundreds of thousands of atoms, possibly of millions.

It provides the biologists with an indubitable specimen of the invisible stuff that is responsible for so many human ills, and if we can learn in intimate detail the ways of the tobacco mosaic virus we may get some important flashes of information on the ways of the virus of the common cold and other hidden enemies of mankind. Many points of correspondence have recently been found, properties in which the plant virus shows characteristics similar to the animal virus. Thus, it is known that the common cold affects many species of animals. Similarly, the tobacco mosaic virus affects tomato, phlox, and spinach plants, as well as tobacco. H. S. Loring, one of Stanley's coworkers, recently extracted a crystalline substance from the juices of diseased tomato plants, and the substance was found to be a protein identical with that extracted from the juices of the diseased tobacco plants. The protein has also been isolated from mosaic-diseased spinach and phlox plants.

Another point of similarity between the tobacco mosaic virus and the virus of animal diseases lies in this: that both may be inactivated and rendered harmless. Thus Pasteur found that by drying the spinal cords of dogs which had died of hydrophobia, he obtained a material which was harmless; and yet it seemed to contain the principle of the hydrophobia carrier, for a person inocculated with the material gained a certain immunity to the disease. Stanley has found that by treating his crystalline protein with hydrogen peroxide, or formaldehyde, or other chemicals, or by exposing it to ultra-violet light, he causes its virulence to vanish. When the virus is rubbed on the leaves of healthy plants, no ill effects follow. And yet the crystals appear to be the same as those of the virulent untreated protein. When they are analyzed by x-ray bombardment they show the same diffraction pattern, when weighed they show the same molecular weight, and, most important of all, when injected into animals they produce an antiserum which

when mixed with solutions of active virulent virus is able to neutralize or render inactive such solutions. There are slight chemical differences, however, and it is Dr. Stanley's idea that the effect of the treatment is to alter certain active groups of the huge molecule—to switch certain towers or ells of its architecture, as it were—but to leave the structure as a whole unchanged. These experiments with inactivation of the tobacco mosaic protein seem to promise results that will be helpful to the human pathologist searching the frontiers of immunization.

Additional support for the idea that the tobacco mosaic protein is a virus was obtained early in 1937 by Stanley and Wyckoff. They found that, instead of depending on chemical means to isolate the virus, they could accomplish the result mechanically with the ultracentrifuge. By whirling a solution of juices from the diseased plants, repeating the process with the heavy precipitate thereby obtained, and doing this over and over again, they found it practicable to separate the activating substance from the mixture. In this way Stanley and Wyckoff isolated the molecule of another plant virus, the infectious ring-spot disease. By the same method they isolated the activating agent of still other vegetable diseases, potato mosaic, severe etch, cucumber mosaic; finding that the concentrations of these viruses in the host differed widely. Most important of all is their demonstration that the activating substance of each of these highly contagious plant diseases is a heavy protein molecule similar in general to the first found, the tobacco mosaic protein of Stanley's pioneering chemical experiments.

But man, whose virus diseases are of *animal* nature, wants to know of the virus that affects animals. Has any research progress been made in that direction? Yes, an interesting beginning, just announced. There is a highly contagious animal disease known as "infectious papillomatosis" which affects rabbits. It causes warty masses to grow on the ears and other parts of its victims, and has been at-

tributed to a filtrable virus carrier. This disease was first described by R. E. Shope; and recently Wyckoff and J. W. Beard obtained some of the warty tissue from Dr. Shope, ground it up, made a solution of it, and subjected this solution to the new technique of the ultracentrifuge. In this way they isolated a heavy protein which when tested on healthy rabbits immediately communicated the disease. But rabbits frequently develop warts which are not infectious, and so as a further test the investigators obtained some of this noninfectious warty tissue, and subjected it to the same treatment. They were unable to obtain from this solution any heavy protein, though repeated trials were made. Apparently the giant molecules flung out of the solution of the infectious tissue are a virus which is not present in other warts. And by weight and measurement the wart virus proves to be a tremendous molecular structure weighing something more than 20,000,000 and measuring about 40 millimicrons in diameter. Thus the first animal virus to be isolated is a larger, more massive, and presumably a more complex molecule than that of the first discovered plant virus, the carrier of tobacco mosaic. But all our evidence points to many similarities among these various disease-carrying substances, and very many lines of research are now being pushed with the tobacco mosaic protein on the idea that it is not only a virus but a representative species of the whole virus family, both plant and animal.

Is it alive? Stanley reminds you that it can be crystallized, a property that we think of as purely inanimate and wholly chemical. He points to the additional fact that it has not been cultured in a test tube. This would seem to say that it is not a bacterium. A few bacteria placed in a nutrient soup will rapidly multiply into uncounted millions, but the crystalline protein shows no growth behavior in a glass vessel, no metabolism, no reproduction.

And yet, observe what happens when it comes in contact with the inner tissue of a tobacco plant or other vege-

table host. Instantly the molecules begin to multiply. An almost imperceptible particle of a crystal will infect a plant, and in a few days the disease will spread through a field, producing an amount of virus millions of times that of the original. It exhibits a fecund ability to propagate itself, to extend its occupancy of space and time at the expense of its environment. Is not this a characteristic of living things?

Perhaps the virus is a molecule of double personality, alive and yet not alive—animated by its environment when that environment is specific to its nature, but passive in any other environment. The discovery of this substance and the elucidation of its properties is one of the most important biological advances of our century. In 1936, when Dr. Stanley presented his comprehensive paper reporting the research to the American Association for the Advancement of Science, the Association esteemed the report the most important on its agenda and awarded Stanley its $1000 prize.

4

The tobacco mosaic protein has certain apparent points of correspondence with the gene. The two appear to be of approximately the same order of size. Both are molecules that in certain surroundings undergo duplication. Both suspend this reproductive faculty over long periods of time without losing the capacity to call it into action when conditions are favorable. The quiescence of genes in an unfertilized egg or in the cells of a resting seed, and the inactivity of the virus when stored in a bottle, are examples of the last-mentioned characteristic.

There is still another parallel. The gene, as we know, is sometimes unstable. Stanley has found a somewhat similar behavior in his crystalline protein. The common form of its disease is known as "tobacco" mosaic, and produces a green mottling of leaves. Recently there was discovered

another strain of the disease which has been named "masked," and a still more virulent form known as "acuba" which shows a yellow mottling. The crystals of acuba strain are larger, its solution is more silky and opalescent, its solubility is lower, and the ultracentrifuge shows that its molecules are actually larger than those of the common tobacco mosaic—they weigh nearly as much as the giant molecules of the rabbit wart disease, approximately 20,000,000. Now the strange finding of recent experiment is this: a tobacco plant suffering from the common form of the mosaic disease may suddenly *change* to the more virulent acuba form. Apparently something happens by which the smaller molecules of 17,000,000 weight attach other molecular groups to themselves to form particles of 20,000,000 weight, and these combinations take place between just the right groupings to produce the acuba effect. In a sense, it is a synthesis. Also it suggests the important property of individuality. Just as each gene, or at least certain genes, seems to carry an individual pattern to control the future development of its organism, so does the molecule of the mosaic disease possess a personality, a nature individual to its structure—being in some instances of the "masked" strain, which is so mild in its symptoms as to be almost unrecognizable; in other instances of the "tobacco" strain, which is serious; in other, of the "acuba" strain, which is highly dangerous; and in still other, of the "lethal" strain, which invariably causes the death of the plant. It seems likely that a single virus molecule may in the course of its history appear in each of the four roles, mutating from strain to strain as it loses or gains features of molecular structure. In these behaviors we recognize a curious suggestion of the mutation of unstable genes.

Oscar Riddle, of the Department of Genetics of the Carnegie Institution of Washington, noting some of these parallels, is inclined to believe that in one respect the gene represents a higher order of organization than the virus.

He points to the teamwork of the genes in the chromosomes as apparently an essential relationship. All the evidence goes to show that the gene must be in association with its fellow genes in order to duplicate, and Dr. Riddle doubts if a single gene alone can perform any function. Indeed, he questions if an isolated gene can be called alive—which is precisely what Stanley questions of his crystalline protein.

But this leads to another question. How "live" is alive?

5

There is a bacterium known as azotobacter, an organism nearly as large as a yeast cell. It lives in the soil, it breathes, it takes in food from its surroundings, it grows and multiplies—all authorities agree that azotobacter is alive. Indeed, it possesses a remarkable faculty which the majority of other species of living things lack—the capacity to fix gaseous nitrogen. The azotobacter is continually taking free nitrogen from the air, and by combining it with certain organic matter absorbed from the soil, it is making ammonia or the equivalent, fabricating that into amino acids, and out of the acids building protein. This faculty is indispensable to life as we know it, for without protein it is impossible to have protoplasm. The ability to form proteins is a test of life.

Recently, at the Academy of Sciences in Moscow, three Russian chemists collaborated in a series of experiments with azotobacter. A. N. Bach, Z. V. Yermolieva, and M. P. Stepanian were the experimenters. They cultured a pure group of the bacteria in a glass vessel, feeding them sugar, and obtained a small output of ammonia. Then the chemists took the teeming microbes, crushed them, ground them, and pressed out the juices. This bacterial fluid could be filtered free of any trace of cell matter. To the clear filtrate the Russians added sugar and bubbled a mixture of nitrogen gas and oxygen gas into the liquid. According to their report, the filtrate produced ammonia. Something in the

lifeless juice was doing what the living bacteria had performed as their unique function.

Professor Bach and his associates explain that the nitrogen fixation in the living azotobacter is accomplished by an enzyme. An enzyme is a catalyst, *i.e.*, a chemical substance which activates and promotes the combination of other substances into new compounds but itself remains unchanged in the process. It is the Russians' idea that their crushing and filtration procedure separates out this organic catalyst, and they point to their experiments as proof that the catalyst is just as potent to perform the synthesis in a test tube as in the living creatures. Indeed, they claim, it is more effective in the test tube, and they cite records which indicate that the yield of ammonia from the filtrate is fifty times greater than that from the living bacteria when fed an equivalent amount of sugar. This very striking difference is explained on the supposition that the living organisms consume much of the sugar to sustain growth and other vital processes, whereas the free enzymes in the filtrate, being "mere" chemicals, have no vitalistic burdens. So they stick to business and turn out a maximum yield.

An interesting series of experiments in this field is now in progress in America. Dean Burk, chemist at the United States Department of Agriculture, visited the Moscow laboratory, spent several weeks in consultation with the Russian investigators, watched their technique, and on his return to Washington set up a similar apparatus to repeat the investigation here. His results will be awaited with keen interest. Confirmation of the Moscow findings by an outside laboratory would mean another step into the dim borderland between the living and the nonliving.

Perhaps the nearest we can come to a definition is to say that life is a stage in the organization of matter. The ascent of life, from azotobacter to man, is a hierarchy of organizations continually becoming more complex and more versatile. And so with the ascent of matter, from the single

electron or proton to the numerous and enormously complicated colony of electrical particles which make up the bacterium—it too is a hierarchy of continually increasing complexity, of relationships, of organization.

Protons and neutrons, with their encircling electrons, associate together to form atoms, but their organization is too primitive to permit any behavior recognizable as life. The atoms, in their turn, group to form molecules of simple compounds—water, salts, carbon oxides—but again the grouping is too limited to operate in ways that class as animate. From these simple molecules more complicated ones are synthesized in nature's unresting crucible, sugars and other carbohydrates, fats and more intricate hydrocarbons. And somehow, in the melee, atoms get joined together in the distinctive patterns known as catalysts, of which the enzymes are a special class. The primitive catalysts may fabricate the first amino acids. Out of these essential acids they build the first proteins, simple ones at first. Proteins associate with other proteins, eventually they join as subgroupings of larger molecules to form what we imagine to be the first genes, and chains of these giant molecules line up or interweave and interlink as chromosomes. And so specialization develops, coordination evolves, the ability to duplicate the pattern, to divide, to multiply, to enter into a dynamic equilibrium of continually moving material and forces—life!

Just where life first appears in this supposed sequence is beyond charting. But perhaps it is not far amiss to think of the turning point as being reached with the emergence of the protein-building catalyst. The gene may be the most primitive living unit. The virus may be the most primitive predator on life. But the presumption is strong that neither of these organizations antedates the selective, assembling, organizing presence of the enzyme. The enzyme may not be life, but it seems to be a precursor of life. And wherever it becomes active may be the place where life begins.

Chapter XIII · MACHINES WHICH IMITATE LIFE

What am I, Life? A thing of watery salt
Held in cohesion by unresting cells
—JOHN MASEFIELD, SONNETS

HERE is a curious behavior which has interested many persons who have seen it. A drop of chloroform is introduced into a beaker of water. You take a fine glass rod and try to puncture the chloroform drop. It resists. But if you coat the tip of the rod with shellac the rod is avidly sucked into the drop. The chloroform acts as though shellac were its food, and as soon as it has fed, *i.e.*, as soon as the shellac is dissolved, the drop manifests its former antipathy to the glass and ejects the rod as so much waste. A living amoeba behaves in much the same way.

But the amoeba can multiply itself. After growth has reached a certain stage its single cell of protoplasm divides into two, and each becomes an individual amoeba capable of independent action, continued growth, and repeated cell division. This is life: activity, growth, reproduction, the continuous passing on of the torch. But there are purely chemical setups which perform in much the same way. For example, a drop of oil may be suspended in water. If you touch it at opposite sides with two small pieces of soda the surface tension of the drop is lowered at the two points

of contact; consequently the surface tension at its equator becomes relatively greater, and the drop neatly divides into two droplets. There are other combinations of material in which inorganic bodies spontaneously bud and proliferate in seemingly lifelike behavior. The action of a drop of yellow prussiate of potash when suspended in a water solution of blue vitriol is an example among several that are known.

The chloroform, the oil, and the yellow prussiate of potash are familiar chemical compounds, and their reactions to the glass, the shellac, the soda, and the blue vitriol are readily explainable in physical terms. There are laws of solution, of surface tension, osmosis, and chemical affinity which fully account for the behavior of these inanimate combinations. Protoplasm is more intricate. Its members are more complex and more varied, and its reactions, therefore, are more complicated than anything we know in the test tube. But may we not suppose that they are physical and chemical changes throughout, that all the essential behavior of life is ruled at bottom by the same laws which govern the drops of chloroform, oil, and prussiate of potash?

It would be a presumption to answer this question with a straight Yes, but the accumulating results in the laboratories steadily point that way and give a hopeful bias for such an answer. I say hopeful because any other answer would be discouraging, not only to biological research, but also to medical practice and to mankind's frail fight for time. If the toll of disease has been cut down and the average longevity of human life extended, it is largely because modern experimenters have believed with sixteenth century Paracelsus that "the body is a conglomeration of chymical matters; when these are deranged, illness results, and naught but chymical medicines may cure the same."

Sir Frederick Gowland Hopkins, a discoverer of vitamins, tells of the remark of a distinguished organic chemist of

the 1880's commenting on his decision to pursue biochemistry. "The chemistry of the living? That is the chemistry of protoplasm; that is superchemistry; seek, my young friend, for other ambitions." But Hopkins and other pioneers of his generation held to their conviction that life is physically reasonable, and the fruits of their research today are eloquent endorsement of the Paracelsian doctrine.

If the hydrogen, carbon, oxygen, nitrogen, and other elements which compose the living body are the same as the hydrogen, carbon, oxygen, nitrogen, and other elements which compose the air, the earth, and the sea, it should be possible to set up chemical and physical arrangements which will duplicate the results of living processes. This has actually been done in several laboratories. No one has been able to construct a mechanism which will exhibit all the kinds of behavior of even the simplest organism, but there are many types of biological behavior which have been isolated and simulated separately. This fact is additional testimony perhaps to the elaborate complexity of protoplasm. Professor Henry A. Rowland used to say to his Johns Hopkins students that he did not know what an atom was like, but, he added, it must be at least as complicated as a grand piano. On this basis we might venture to postulate the microscopic amoeba as "a conglomeration of chymical matters" at least as complicated as a symphony orchestra or, perhaps better, a convocation of symphony orchestras. Dr. Clark L. Hull, in whose laboratory at Yale I saw demonstration of many different types of machines which imitate thinking processes, admitted the primitive crudity of these gadgets. They are simplifications, analogues, groping approximations—but they do demonstrate the fact that it is possible for nonliving matter to execute results of a kind which we are accustomed to associate only with the living. And that, no matter how feeble the effect nor how limited its range, is a gain—a step toward the unmasking of living protoplasm.

I

The heart is a pump. But is there any imperious necessity that it be a living pump? Early in the nineteenth century the French physiologist C. J. J. LeGallois suggested that "if one could substitute for the heart a kind of injection . . . of arterial blood, either natural or artificially made . . . one would succeed easily in maintaining alive indefinitely any part of the body whatsoever." It is a rather telling footnote to the magnitude of this "if" that more than 100 years passed before an inventor was able to surmount the difficulties of the requirement and produce an apparatus that would substitute for the heart as an engine of circulation. In the interim, various brilliant feats with severed organs were attained, solutions capable of sustaining life were compounded and used as media for such transplantings; but in even the most successful of these experiments the separated organ survived only a few hours. It was not until the year 1935 that the program proposed in 1812 by LeGallois was realized. In June of 1935 a brief scientific paper, signed by Alexis Carrel and Charles A. Lindbergh of the Rockefeller Institute for Medical Research, announced the remarkable results obtained from a perfusion pump of Colonel Lindbergh's design, "a model that has for the first time permitted an entire organ to live outside of the body."

Anything connected with either Lindbergh, the hero of transatlantic flight, or Carrel, America's first winner of the Nobel Prize in Medicine, was good for a headline, and this news of the laboratories immediately jumped from the inconspicuous inner pages of the weekly journal *Science* on to the front pages of the daily newspapers. But when the editors and reporters tried to shape the story, puzzled by the connection of the aviator with this technical medical business, they found that the research itself, rather than

the personal anecdote of the inventor which they vainly sought, was the big news.

A thyroid gland had been removed from a cat, installed in a glass chamber, and for more than twenty days this excised organ, perfectly protected against bacterial infection, had lived an apparently normal life in its artificial environment. Its arteries pulsed, its cells grew and multiplied, its secretions flowed, all the usual functions of life continued—thanks to the unfailing regularity of the perfusion pump. So long as this artificial heart circulated its artificial blood, sending life-giving nutrients and oxygen to the imprisoned organ, the gland flourished. And so with other organs. There were twenty-six experiments in all, using kidneys, hearts, ovaries, spleens, and suprarenal glands, in addition to thyroids, and in each case the perfusion pump proved itself competent for the task. There are many reasons to believe that LeGallois's full conception may now be realized: that science at last has at hand an apparatus for maintaining alive *indefinitely* any part of the body whatsoever.

This means that those parts concealed within the mantle of flesh may now be brought out into the transparency of the glass tube and there be followed through every detail of functioning. Three fairly obvious applications suggest themselves as possibilities.

First, the normal organ may be studied to see how it operates, how it is affected by changes of diet, by drugs and other stimuli, and what conditions are optimum to its well-being. In experiments with a thyroid Dr. Carrel demonstrated the feasibility of this technique. By changing the content of the circulating fluid he showed that he could change the behavior of the transplanted organ which it irrigated. When the fluid was diluted the thyroid responded to this starvation treatment by losing weight progressively; but when the fluid was enriched by generous additions of a

growth-producing medium the gland grew rapidly. These results suggest endless possibilities for experiment with normal organs.

Similarly, a diseased organ could be installed in glass and watched through the course of its malady, to discover the nature of the disease and explore the possibilities of a cure. It might be possible to remove a diseased viscus, such as a kidney or a thyroid, and by cultivating the thing *in vitro* learn more in one experiment than could be uncovered in years of groping in the dark of pain-racked human bodies. Diseases of the arteries, which account for so large a section of the death roll, should lend themselves to experiment in the transparent environment of the glass chamber.

Still a third practical application would be the use of the perfusion pump to cultivate glandular organs for the sake of their secretions. During thousands of years man has practiced this exploitation of the submissive cow, cultivating the whole animal for the reward of the secretions from her lactine glands; it should require, therefore, no wrench of the imagination to picture the more specialized practice here suggested. The pancreatic gland produces the indispensable hormone known as insulin which aids the animal body in its utilization of sugar. When the human pancreas fails, the victim of this lack dies unless the necessary insulin is supplied from some other organism. Today there is a considerable industry which makes a business of extracting insulin from the pancreas of freshly killed sheep and other animals and marketing it for the benefit of persons suffering from diabetes. But with the technique provided by the Carrel-Lindbergh research, the pancreatic gland may be transferred alive to an assigned glass compartment and there be maintained in perfect health by the continuous flow of the rich fluid circulated by the perfusion pump—yielding meanwhile an output of insulin as standardized as the output of milk is from a scientifically managed dairy. The current practice of insulin extraction

may be for the present more practicable commercially, but the picture here suggested is possible theoretically, and may in time be realized.

It would seem, therefore, that there is no imperious necessity that the heart be a living pump. Lindbergh's mechanical pump—made of glass, actuated by the pressure of compressed air, which pressure is released into the pump in pulsating sequence through a revolving valve operated by a diminutive electric motor—does just as well so far as the bare necessities are concerned. The living heart, hidden within the flesh and activated by its own living mechanism, is more compact and more convenient; but the mechanical heart has demonstrated that it can do the job. It can circulate a fluid (free from bacteria) which will sustain life, and there is every reason to believe that it can continue such a process indefinitely.

2

Biological models are of two kinds. There are, first, those like the perfusion pump, which are designed as working substitutes for living organs whose operation is fairly obvious. The second type of biological model springs from a different motive. Here the attempt is not to provide a practical substitute for an essential organ, but rather to explore and understand the mystery of the organ itself. In the first type the model is auxiliary to a research on some other problem. In the second type the model is the problem; it embodies the biologist's theory of what he is trying to understand, and indeed the main purpose of the model is to test the theory.

For example: in the living organism the observer encounters a process which seems comparable to that of water running uphill. Briefly, it is this. Protoplasm exists as a jellylike liquid that invariably gives an acid reaction, whereas the blood stream which ceaselessly irrigates the cells is alkaline. The acidic protoplasmic interior of each

cell is separated from its alkaline surroundings by only a thin membrane, and through this membrane nutrients are continually diffusing inward from the blood into the protoplasm, and waste products are continually diffusing outward from the protoplasm into the blood. In spite of these interchanges, the acid of the protoplasm and the alkali of the blood never seem to meet and neutralize each other—though a normally high affinity between acid and base is one of the most universal and powerful relations known to chemistry.

The situation is still more emphasized by the accumulation of certain substances. Every living cell shows a tendency to take in potassium, though blood and other media which feed the cell are habitually poor in potassium. The blood is rich in another element, sodium, which is similar in general properties to potassium; this exists there mostly in the form of sodium chloride (which is responsible for the salty taste of blood). But the protoplasmic stuff inside the cell will accept little—in some cases none—of this wealth of surrounding sodium. It takes potassium, from an environment that is meagerly provisioned with potassium, and excludes sodium, though its all-embracing medium is teeming with that prolific element; and it continues to do this throughout its entire process of growth. In some instances the potassium concentration within the cell is forty times that of the medium outside, and yet the flow of potassium continues persistently from outside to inside. It suggests something of a paradox: as though a head of water which was gauged at a pressure of 100 pounds to the square inch should steadily flow upward to a tank where the pressure was 4000 pounds to the square inch.

This strange capacity of the living organism for working, as it were, against the energy gradient has long preoccupied the attention of biologists and philosophers.

Philosophers pointed to it as evidence of the presence of a "life force." It goes to show, they said, that in the cell there

is something outside the sway of chemistry and physics, something that can outwit the second law of thermodynamics and attain upstream motion in a world where the order of energy changes seems everywhere downstream.

Biologists looked to their experiments. By what "conglomeration of chymical matters" could such a system operate—a system in which "to him that hath shall be taken away even that which he hath"? In other words, by what chemicophysical arrangement could the selective permeability of the cell be explained?

Theories were proposed. It was suggested that the potassium enters the cell in soluble form, and when inside combines with other elements to form an insoluble compound which, because of its indiffusible nature, cannot escape. Another explanation called into use the Donnan equilibrium, a complicated law of chemical energetics which might account for the apparent paradox. Neither of these theories was derived from experiment. They were offered simply as hypothetical explanations, awaiting test.

3

For one of the most successful attacks on this riddle we turn again to the Rockefeller Institute for Medical Research, to the work there of W. J. V. Osterhout and his associates. Dr. Osterhout came to the institute several years ago from Harvard University, where he was professor of botany; and perhaps his past experience predisposed him to go to the plant world for the most fitting subject for his search into the chemical mechanism of life. Most protoplasmic cells, both plant and animal, are of microscopic size. Special techniques have been worked out for the microdissection of these minute units, some of them of marvelous and ever-fascinating deftness; but protoplasm is so sensitive that one can never be sure of the integrity of the ruptured cell. The content of injured protoplasm cannot be assumed to be the same as that of normal proto-

plasm. Osterhout wanted to take samples of the interior fluid and analyze them; he wanted to introduce different conditions into the cell and see how it reacted; he wanted, in effect, to get inside this complicated living machine without injuring it; and for this kind of venture he needed a big machine.

There is a marine plant known as valonia. It is of the algae, one of that innumerable horde whose most common representative is the green scum which floats on ponds; under the microscope the scum shows itself to be made of minute cells joined one to the next in long filaments. The valonia cells, however, are not so sociable. Each lives its life apart and each attains gigantic size—for a cell. A full-grown valonia may be larger than a pigeon's egg. And yet it is a single cell of living matter—a unit organism, like an amoeba, and not a composite, like a man. Its general structure is easy to describe: (1) a firm outer wall of cellulose, inside of which is (2) a thin layer of protoplasm clinging to the cellulose surface like paper on the wall, and (3) sap filling the interior cavity. Valonia lives in the sea, and an environment of sea water appears to be as indispensable to it as an environment of blood is to the cells of the human body. Therefore, to represent the complete establishment we must add the final element, (4) sea water outside the cell.

Osterhout and his aides found this marine plant a pliant subject for their study. Hundreds of valonia cells were obtained from the favorable waters off Bermuda and installed in vessels of sea water in the laboratory. To gain access to a cell interior the experimenter punctured its wall and protoplasmic membrane with a fine glass tube that had been ground to a needle point. In a related alga, halicystes, two tubes were inserted and left in unused until the cell had recovered from the invasion, repaired the wound, and resumed its normal functioning. Then a series of experiments began. Through these diminutive tunnels it was

possible to draw out samples of the sap; indeed the entire contents of the vacuole were removed in some experiments. It was possible to introduce other solutions, to dilute the sap, or to replace it entirely.

But the significant discovery, from the point of view of our discussion, was disclosed by analysis of the sap of valonia. It was found to contain accumulated potassium, in the proportion of forty parts in the sap to one part in the sea water. This accumulated potassium, moreover, was not locked up in the form of insoluble compounds, but was dissolved in the watery sap. Nor were the proportions those of the Donnan equilibrium. Experiment thus demonstrated that both of the proposed theories of this queer selectivity were mistaken, and it was evident that some other means of accounting for the behavior must be sought in the cell structure or composition.

The cellulose wall was dismissed from consideration, for it proved to be permeable in either direction; apparently it is simply an outside skeleton to provide a supporting structure for the coating of protoplasm inside. In the protoplasm, therefore, must be the agency that determines what enters and what is excluded.

The protoplasm of valonia, as I have mentioned, is a thin layer—less than the two-hundred-and-fiftieth part of an inch in thickness. Despite this, the layer shows stratification: first a film of lipoid or oily material constituting its outer surface, then a thicker region of watery material, and inside another surface film of lipoid.

Tests showed that it was the surface of the protoplasm that played the dominant role in this biochemical drama. When the oily skin was broken, all the electrical effects of the cell ceased, all its power of selective permeability disappeared, the accumulated potassium flowed out into the surrounding sea water until the sap within contained precisely the same dilution as the water without, and the cell died. It was not necessary to break through the full

thickness of the protoplasm. The slightest rupture of its almost impalpable lipoidal film was sufficient to disrupt the finely balanced machinery and destroy its capacity for trapping some substances and excluding others.

The valonia cell, thus dissected, may be diagrammed in cross section roughly as follows:

The living cell

Would it be possible to imitate this living apparatus? Dr. Osterhout's studies of the cell had led him to formulate a physicochemical theory of its operation, and if true the theory should be demonstrable. There is no need here to elaborate the theory in its entirety but we may note a few salient points.

In the first place, it was known that potassium, sodium, and other electrically active elements move in an aqueous solution as dissociated atoms—that is, as ions, each bearing an electric charge and, therefore, each constituting a moving unit of the electric current. But oils, fats, lipoids do not conduct the electric current, and experiments with the protoplasmic surface showed that this is true of that particular lipoid. Electrolytes, therefore, must penetrate this surface in some form other than as dissociated atoms or ions.

But potassium and sodium exist in the sea in alkaline compounds (as well as in the familiar salts) and Osterhout turned his attention to these. If there were an acid in the protoplasmic surface it might combine with alkalis of the

sea to form salts of potassium and of sodium, and these salts might permeate the oily film and pass through as whole molecules.

However, the rate of transport varies from element to element. It is well known that certain solutes move more readily than others. This quality depends on their "partition coefficients," and the partition coefficient depends in turn on the ionic radius of the element—the greater the radius the more rapid is the motion. It happens that the ionic radius of potassium is greater than that of sodium. We thus arrive at a purely chemical explanation of the "preference" of the cell for potassium.

The potassium passes through the protoplasmic layer in the form of a potassium salt, but as soon as it reaches the interior and comes in contact with the sap it changes again. The sap contains carbonic acid, for which the potassium has stronger affinity. So the potassium drops the atoms which it took on from the protoplasm and contracts a new union to form potassium hydrocarbonate, a salt which immediately dissolves in the watery sap. Thus the carbonic acid of the sap is continually being neutralized by the inflowing potassium; and if this were the whole story the process would be short-lived.

But there is another operation continually at work. The cell is respiring, that is, taking in oxygen and sugar and burning them to release energy and form carbon dioxide. Some of this carbon dioxide (also known as carbonic acid gas) is continually uniting with water in the sap to form carbonic acid, and thus the acidity of the sap is steadily renewed. In consequence there is always acid within to combine with the entering potassium. Indeed, the acid may be pictured as a sort of chemical magnet attracting the potassium, or, better still, as a chemical pump sucking it in. The acid would react just as effectively with sodium, if the sodium were quick enough to get through the lipoidal film in sufficient numbers. But the peculiar nature of potassium gives it

greater penetrating power, and thus a higher ratio of accumulation.

The test of this theory was a model. In the living apparatus there were three essential phases: (1) the sea water, (2) the cell sap (both aqueous solutions), and (3) the protoplasmic surface (a nonaqueous phase separating 1 and 2). Clearly, the model must contain parts corresponding to these three phases. It was not necessary, however, to construct a hollow globule the size of a pigeon's egg in order to simulate the mechanics of the cell. All that was required was to concoct an artificial sap and an artificial sea water and separate them by an artificial protoplasmic surface.

To simulate the protoplasmic surface Osterhout selected two well-known carbon compounds, guaiacol and p-cresol. He mixed them in proportions 70 per cent of the first and 30 per cent of the second. The result was a heavy oily liquid, nonaqueous, impervious to water, and containing an acid.

To simulate the sea water he dissolved equal amounts of caustic potash (potassium hydroxide) and caustic soda (sodium hydroxide) in distilled water. Since both compounds are alkalis, the solution was alkaline.

To simulate the cell sap he bubbled carbon dioxide through distilled water. Some of the gas combined with the water to form carbonic acid, and thus the solution, like the sap, was acidic.

We now have three artificial liquids. To make our model we must separate the acid solution from the alkaline solution by the nonaqueous oily fluid. A simple arrangement in a glass beaker accomplished this. Into the beaker Dr. Osterhout first poured the guaiacol-p-cresol solution, sufficient to cover the bottom to a depth of two or three inches. Then he lowered a short section of a large glass tube into the beaker, and supported it there permanently with the lower end of the tube protruding slightly into the guaiacol-p-cresol solution. Into this inner tube he poured the acid solution, into the beaker outside the tube he poured the

alkaline solution, and thus the model was complete. The wall of the glass tube prevented any direct intercourse between the artificial sap within the tube and the artificial sea outside. The only possible communication was through the artificial protoplasm. If any of the alkalis of the artificial sea could combine with the acid of the artificial protoplasm (as postulated by the theory) then some of the electrolytes of the "sea" ought to pass through the non-aqueous liquid and up through the open end of the tube into the "sap." The model may be outlined in cross section, thus:

The artificial cell

This artificial cell worked. Just as in the living cell, so here in this nonliving model potassium and sodium accumulated in the sap, and the potassium concentration increased more rapidly than the sodium concentration. By lowering a small glass tube into the "sap" and continually bubbling carbon dioxide gas through it, the acidity of this internal fluid was maintained. Eventually the artificial cell reached a steady state at which the concentration of potassium and the lessened concentration of sodium attained a fixed ratio to the water content of the sap—which is precisely what happens in the living valonia cell. A purely physicochemical model of a living process!

4

The model just described simulates one general property of the living organism—namely, its permeability. But in a

live cell many other processes are operating at the same time. Each seems to depend on a train of physicochemical reactions, and by separating the functions and isolating them in individual models, biochemists have been able to imitate many of these processes in other artifacts.

In experiments conducted at the Desert Laboratory of the Carnegie Institution of Washington several years ago, D. T. Mac Dougal made artificial cells of cellulose capsules, lined them with jellylike mixtures, and filled them with an acid sap. These cells maintained their acidity for days in alkaline solutions, and exercised selective absorption of sodium, potassium, calcium, chlorine, and nitrates from soil solutions—activities similar to those of living root hairs.

At another Carnegie Institution laboratory, that of Plant Biology in California, H. A. Spoehr has set up a cell model which respires. It takes in oxygen and sugar and combines these materials to form carbon dioxide and water, which is precisely what the living cell does. In the living cell, iron is present and is believed to serve as the catalyst which facilitates the breakdown of sugar and its oxidization to water and carbon dioxide at ordinary body temperature, without the chemist's usual aid of heat or strong acids. Similarly, in his model, Dr. Spoehr includes an iron compound for the same purpose, and the reactions take place under comparable conditions of body temperature and absence of strong reagents—an impressive analogue in a glass cell of the basic act of metabolism.

At the University of Chicago, in its laboratory of general physiology, Ralph S. Lillie is working with a model of the nerve cell. His model consists of an iron wire immersed in a strong solution of nitric acid—a purely inorganic chemical system. But Dr. Lillie finds that the response of this strip of passive iron to various stimuli—such as touching it with a base metal, jarring it, bending it, or scraping it with a piece of glass—is very similar in its conditions and general

features to the response of a nerve or other sensitive protoplasmic system. The irritability of the nerve shows itself when an electric current is passed through it, and similarly the wire shows a closely analogous type of responsiveness to the electric current. In both cases there is a trigger effect. The stimulus must reach a certain magnitude before any response is given, but when it is given the response is complete. That is to say, both the living cell and the nonliving wire behave in the "all-or-none" manner characteristic of nervous action. Experiments show that when the wire is first placed in the acid a thin surface film immediately forms which is analogous to the surface film of protoplasm. In both cases the film is impermeable, electrically polarizable, and chemically alterable. Dr. Lillie attributes the irritability of the iron and of the protoplasm alike to physical and chemical changes which occur in their respective surface films.

The oil films on water with which Irving Langmuir has been experimenting, as reported in Chapter X, provide still another model of the living setup. Here the film is made to approximate very closely the surface conditions within and without the cell, and permeability seems to be related to the density of the monomolecular layer—ranging from the impermeable state of a two-dimensional solid to the very permeable state of a two-dimensional gas. There seems to be endless opportunity for experiment with these models.

5

But a model does not have to be an actual physical apparatus or a system of chemical materials in vessels. The physicist has long been familiar with paper-and-pencil studies of physical systems; and with the application of mathematical techniques to biology, the same practice is becoming increasingly helpful in exploring the fundamentals of living systems. An outstanding example of this is pro-

vided in the work of another scientist at the University of Chicago, a mathematical biophysicist, Nicolas Rashevsky. Dr. Rashevsky is one of a small group of pioneers who have essayed the task of building "a complete and consistent system of mathematical biology," approaching this formidable undertaking by means of paper-and-pencil models of the cell.

The living organism is so complex that at first thought this would appear to be a hopeless task. Forms, sizes, and structural details vary widely, from the huge valonia cells to the microscopic bacteria, from the long nerve cells to the floating red corpuscles of the blood stream. Essentially, of course, all cells are systems of protoplasm, and most of them are characterized by two general features: an inner structure, the nucleus, surrounded by the cytoplasm. But the nucleus, as we have seen, is a complex of chromosomes, which in turn are made up of smaller units, the genes; and similarly, under the microscope, the cytoplasm exhibits differentiation, vacuoles, fat globules, mitochondria, all in ceaseless motion, bubbling, flowing, living. By what mathematical magic may the physicist hope to approach this restless intricacy and sort out its phenomena into their physical sequences?

By the well-known strategy of abstraction, answers Dr. Rashevsky; that is, by picking out the essential features and centering attention on them, ignoring for the time the other phases. This is the method by which physics mastered other complexities. Thus Newton's law of gravitation was derived from a study of the problem of two bodies. He considered the motion of a planet in the Solar System as though the planet and the Sun were the only gravitating bodies in the sky, and from that abstraction, that simplification of the complicated pattern of many encircling planets, the great generalization was arrived at. With the fundamental principle expressed in a law, it was possible for later mathematicians to compute the mutual disturbances of the other

planets very precisely—indeed with such exactitude that the existence of unknown planets was thereby disclosed, and their positions indicated so definitely that when searched for in the heavens the predicted bodies were found. These results were a triumph of precision, and yet the method rests in the first place on a simplification which ignored many obvious features.

The mathematical attack on the living cell proceeds by the same method. Just as Newton adopted the relation between the one planet and the Sun as the "essential" in a complex of many relations, so the mathematical physicist must select from among the myriad aspects of living matter those that rate as the "essentials" of the simplest possible system.

Of the multitude of features which enter into a description of the living substance, which shall we take as the irreducible minimum? Some cells have walls, others do not—so we shall not require a cellular wall in our model. Most cells have nuclei, but a few varieties do not—therefore we need not include the nucleus as an essential. And so with the vacuoles, chloroplasts, and other differentiations of the cytoplasm—as they are not in all cells, we leave them off the list of requisites. Retaining only those features which are common to all, Dr. Rashevsky draws up his bill of essentials as follows:

"We conclude that a cell is essentially a small liquid system, a drop, in which occur some chemical reactions that result in growth. The necessary substances for these reactions diffuse into the cell from the outside, with some of the products of the reactions diffusing from the inside out. This growing drop, whenever it reaches a critical size, divides in two, each half growing again, and so on. Moreover, division is the only method by which new drops may be produced. No drop is formed spontaneously, although all necessary substances may be present in the surrounding medium. *Omna vivum e vivo; omnis cellula e cella* [all life

comes from life; all cells from cells]. We are thus led to a physico-mathematical theory of such droplets as a first approximation to a theory of the cell. And this is no longer a hopeless task."

The task is to justify within the laws of physics the observed behavior of these simplified cells. Can such drops show growth behavior and reproduction behavior? Yes, concludes Dr. Rashevsky, if we admit certain fundamental assumptions.

We must assume (1) a drop immersed in a liquid medium, like a cell of protoplasm afloat in the sea. We must assume (2) that the surrounding medium contains in solution the materials which react and recombine to form the substance of the drop. We must assume (3) that this drop substance, however, is not soluble in the surrounding liquid; or else that the drop is surfaced with a film impermeable to the interior substance but easily permeable to materials outside, which enter by diffusion and participate in the internal reactions.

If these postulates are accepted it can be shown that differences in concentration of materials will immediately be set up. Certain materials (corresponding to the food of the living organism) are continually passing into the drop and being utilized to increase its substance, while certain other materials, by-products of the internal reactions (and corresponding to the secretions of waste from the living cell) are continually flowing out of the drop. In general, the "food" concentration will be greatest in the outside medium, and greater inside near the surface of the drop than at its center. Corresponding conditions for the "waste secretions" will be in reverse order—that is, these by-products will be most concentrated at the center of the drop, less concentrated at its surface, and least concentrated in the medium outside.

The differences in these concentrations are highly important. Indeed they are the controlling factor in the behavior

of the drop. If the diffusion of food materials inward is more rapid than the diffusion of waste secretions outward, then the drop increases in size, *i.e.*, *grows*. With growth comes increase in the difference between the concentrations. The differences become greater as the size of the drop becomes greater, and the effect of these disparities is to set up forces which tend to divide the drop, to break it into smaller units, and thus reduce the magnitude of the differences. When a certain size is passed, these forces of disruption get the upper hand and the drop automatically bisects into two drops, *i.e.*, *reproduces*.

What determines this critical size? Many items enter into the tug of war—diffusion constants, permeability rates, temperature, surface tension, rate of internal reactions (metabolism)—all well-known quantitative physical entities. Thus we have reached a purely mathematical basis for growth and reproduction.

While each of the foregoing entities is expressible in terms of exact measurement, the task of measuring all of them and drawing an instantaneous mathematical picture of the entire system of even a single drop is beyond the power of human intelligence. However, to test the theory, this complete analysis is not necessary. The modelmaker may take the outstanding feature—respiration, for example, since in many living cells we observe that the respiratory rate far exceeds all other forms of metabolism. Reckoning thus, Dr. Rashevsky finds that the critical size of the drop is of the order of a globule with a radius of $\frac{3}{100}$ millimeter (about the three-thousandth part of an inch). And when we turn to living material we find that the critical size thus derived theoretically is well within the observed range. Living cells rarely are larger than one-tenth, or smaller than one-thousandth, millimeter radial measurement, in spite of wide differences in their physical make-up.

If the theory be correct, we should expect to find that drops with high rates of metabolism should be of smaller

size than those of low. This seems to be borne out in living forms. In the human body, the cells of the liver are slow takers of oxygen, and they are among the largest cells. In the brain the lower cortical layers are made of large cells, and the higher cortical layers of small cells; evidence seems to show that these small brain cells have a higher rate of oxygen utilization than the large cells.

From the simplified case of the one-phase drop the mathematical biophysicist proceeds to more complicated systems: to two-phase drops (corresponding to cells having nucleus and cytoplasm) and then to colonies of drops. The tendency of cells to group together, to colonize into a composite like a fish or a man, seems to be associated with irritability; the greater the degree of irritability of the cells, the more pronounced is their communistic tendency. And irritability, in turn, is associated with permeability, that physical factor through which the environment of the moment exerts its influence.

There is, however, something not wholly of the moment: it is the property that physicists call hysteresis. It is the property exhibited by a metal wire which has recently been twisted. The twisted wire will behave differently from a fresh wire, apparently "remembering" its experience, but if you wait long enough it may "forget" and not behave so differently. The same "memory" faculty enters into the behavior of the liquid drops.

This is suggested by the fact that if the environment of the drops is changed the behavior of the drops will change —but the same environmental change may produce different response changes, depending on the present configuration or state of the drops, which in turn depends on what has happened to them in the past.

As Dr. Rashevsky explains it: "The reactions of such a system to the same environmental change will vary. They will depend on its 'history,' or, to be still more anthropomorphic, on its 'previous experience.' In a formal way,

however, this is a characteristic of the behavior of all organisms, particularly of the higher ones 'endowed' with a highly developed brain. This dependence of reaction on previous experience we attribute to learning. And, from a purely formal point of view, learning is nothing more than a particular kind of hysteresis. Thus our systematic mathematical study of biophysical phenomena has led us in quite a natural, we may say almost synthetic, deductive way, from the elementary general properties of unicellular organisms to a mathematical study of behavior of higher animals and man!"

The test of theory is experiment. If learning is nothing more than a particular kind of hysteresis, and hysteresis is a common property of material systems, it should be possible to construct models which will learn. Several experimenters have been working with this idea, and claim a modicum of success for their mechanisms—as will appear in our next chapter.

Chapter XIV · THINKING MACHINES

> If an army of monkeys were strumming on typewriters they *might* write all the books in the British Museum.
>
> —ARTHUR S. EDDINGTON, THE NATURE OF THE PHYSICAL WORLD

How many monkeys would be required, how many years they would take, how many tons of paper they would waste before hitting the right keys—these are not specified in the bond, and we may guess that the number in each item would be almost incredibly great. But one feature of the picture is specific, and that is the accidental nature of the process. In their monkeying with the keys the animals just happen to hit off *Hamlet*, the *Ode on a Grecian Urn*, Sir Isaac Newton's *Principia*, and the other works which are treasured in Britain's greatest library. In the imagined situation the monkeys may be regarded as so many forces of the environment, like sunshine and the rain. Indeed, a prolonged fall of hailstones whose masses were sufficient to depress the keys without demolishing the typewriter mechanism should do just as well as the monkey strumming. Thus it might happen that nonliving matter provided the actuating control of the typewriter. Logically we could say that the typewriter itself composed *Hamlet* in response to the changing configuration of the environment. We might

even describe the changing configuration as the stimulus or inspiration of the writing.

From such "nonsense"—and it seems implicit in the modern obeisance of the physical sciences to the law of probability—we are led to the presumption of the thinking mind as the reacting mechanism in a perpetual give-and-take between itself and outside forces. Just as the chance strumming of the monkeys on the typewriter might produce *Hamlet*, so the chance strumming of external nature on Shakespeare may have produced *Hamlet* in the first place. The peculiar physicochemical instrument which we call the man Shakespeare was necessary to the production of the poetic and dramatic effects resulting from nature's impacts, just as the peculiar mechanical instrument which we call a typewriter is necessary to the production of the typed effects resulting from the monkeys' strumming. The monkeys could produce no manuscript from sewing machines, though they might in a multibillion years produce a useful suit of clothes in the Prince Albert style. Similarly, nature could get no verses from Isaac Newton, but it did draw the *Principia.*

Some years have passed since the English philosopher C. D. Broad thought to blast the claims of the mechanists with his verdict: "If a man referred to his brother or his cat as an ingenious mechanism, we should know at once that he was either a fool or a physiologist." If Professor Broad were to pontificate today he might add the biochemist and the psychologist to his list of alternatives.

The biochemist proceeds on the hypothesis that mechanism is the basic principle of nature. It may be a fiction, but it is a useful fiction, indispensable to a chemist—and so he proceeds to apply the law of cause and effect *as if* it were true. The behavior of salts, acids, and alkalis in the test tube follows as if the law were true: then may not the same law govern the behavior of living salts, acids, and alkalis in the bodies of plants and animals? Much

evidence points that way. Biological behavior includes many properties, such as circulation, respiration, digestion, irritability, growth, and reproduction, which have been imitated quite successfully in the laboratory by nonliving models, as we have seen. But biological behavior includes also certain other processes, such as thinking, which seem to belong in a different category. Are these mental phenomena different—are they outside the rule of chemical formulae, beyond dominion of its "great, eternal, iron laws"?

"At one time I thought so," answers the Cambridge University biologist Joseph Needham, "and doubted whether biochemistry and physicochemical study of life could have anything to say about phenomena usually regarded as essentially not physicochemical. It seems to me now that after its own manner it may have everything to say. Let us take, for purposes of exposition, a thoroughly extreme case. Some day some group of biochemical investigators may prove that a deficiency of sulphatide phosphorus and a high oxidation-reduction potential in a certain area of the cerebral cortex is invariably associated with the creation of great poetry. Obviously such a suggestion is as wild as can be, but it is nevertheless a legitimate extrapolation from facts already known."[1]

The psychologists are less unified than the biochemists, both in method of approach to mental phenomena and in the variety of their interpretations; but their outlooks are predominantly mechanistic. One leading school, the psychoanalysts, infer a subjective mechanism in which certain subconscious desires and impulses are the mainspring of conscious thinking. The reality of mind is not denied, but its rational elements are everywhere under the drive of its irrational forces, leaving very little if anything to the free will of the individual.

[1] The quotation is from *The Sceptical Biologist*, an exciting book in which Professor Needham explains his qualification "after its own manner" in interesting detail.

Quite in contrast with this subjectivism of the psychoanalysts is the wholly objective technique of another group of psychologists, sometimes known as the behaviorists. These objective psychologists do not bother to investigate thoughts, dreams, desires, consciousness, the subconscious —all those items dear to the psychoanalyst. Their ideal is the modern physicist's attitude of considering only "observables"; and since thoughts and subjective states cannot be seen, they confine their analysis to the behavior of the individual. How does he act? how does he react to certain events? how does his reaction change when the stimuli change? in a word, how does he behave? When a button is pushed and the automatic elevator stops at the floor indicated by the button, we do not say that the elevator thinks out the problem of selecting the floor. It stops because its mechanism is set to stop. Similarly, says the objective psychologist, with human behavior. A certain sound, a certain sight, a certain odor are as so many push buttons to the living mechanism, and the response of the man is as mechanical as the response of the elevator.

But the elevator response is completely standardized. It never varies from a fixed pattern, whereas human behavior exhibits the concept of choice. Pushing button 16 always results in a stop at the sixteenth floor, but waving a red flag within sight of a human being does not always produce the same effect. The red signal may cause him to stop short and look and listen, sensing danger ahead. Or it may cause him to run forward joyously and welcome the "comradely" symbol of communism. Or it may evoke curses and scowls and cause him to advance menacingly and seize the "hated" flag. In the Harvard Stadium the crimson banner would inspire still different patterns of behavior. Over an auctioneer's door it would carry yet another meaning and call forth other responses. Can the mechanists build a machine that will not only respond to red, but learn

the different meanings of red, and respond appropriately according to the significance of the symbol?

Yes, I believe we could, answers the behaviorist.

Then you could actually build a mechanical mind—one that would exhibit emotions of fear, sentiments of loyalty, thoughts of aggression and acquisitiveness, all the roll call of mental responses evoked by the symbolical use of red?

Call it what you will, answers the behaviorist, we should be inclined to call it a habit machine, a mechanism operating according to the laws of the conditioned reflex.

I

The principle of the conditioned reflex has been recognized since the time of Plato, but its current applications to psychology stem from the work of the Russian physiologist Ivan Pavlov. Many years ago Pavlov began to investigate what happens in a dog's body when food is offered it. The mere sight of a chunk of meat causes the gastric juices to flow, and by means of delicate operations Pavlov gained access to the stomachs of dogs and made measurements of the quantities and velocities of these flows under various conditions. Then he hit upon a more obvious and less difficult technique. The sight of food also causes the mouth to water; why not observe and measure this? So Pavlov turned to the new criterion, and his recent and more famous work has been in what an inelegant commentator calls "the science of slobbering."

It is unnecessary to recount in detail the story of these Russian experiments. They have formed the theme of writings and discussions almost innumerable, and my readers, I feel sure, are well acquainted with the process by which the physiologist showed the purely automatic nature of the dog's responses. Since, however, certain parallels are to be pointed out in this chapter, it will be helpful to recall very briefly a few of the fundamental definitions. The

offering of the food to a hungry dog, Pavlov calls an "unconditioned stimulus"; the flow of saliva in response to this, he calls an "unconditioned reflex." The process of ringing the bell simultaneously with the offering of the food, he calls "conditioning." The sound of the bell is a "conditioned stimulus," and the mouth-watering which responds to a conditioned stimulus is a "conditioned reflex." An agreeable stimulus, such as the food offering, is "excitatory," while an unpleasant one, such as the taste of disagreeable food, is "inhibitory." The brain is the clearing-house into which continually flash these messages of the senses, some of them excitatory, some inhibitory. Whatever is learned, thought, imagined, felt, or forgotten is the result of this perpetual interplay of excitations and inhibitions.

"I write best while wearing a checkered waistcoat," confesses a certain popular author. But do not call it artistic temperament, say the behaviorists; the gentleman has simply been conditioned to the plaid vest—it might just as well have been a helmet and buckler or silk pajamas. He is like the man in John Locke's story who learned to dance in a room where an old trunk stood; thereafter his dancing was conditioned to that stimulus and he never could dance well except in the presence of a trunk of similar appearance. Many idiosyncrasies are explained by this Pavlovian hypothesis of the brain as the automatic switchboard of a completely automatic machine.

And not only idiosyncrasies, but also such faculties as reasoning, insight, purpose are resolved by this same hypothesis into conditioned reflexes. Though the difference in *degree* must be measured in units comparable to light-years in magnitude, this behavioristic interpretation holds that Beethoven's composition of the Ninth Symphony and Leverrier's discovery of the planet Neptune are processes of the same *kind* as the dog's salivation at the sound of the bell. Since the dog's reflexes appear to be mechanical, the objective psychologist argues that man's more compli-

cated intellectual and emotional activities similarly are mechanical.

"It is only a question how the material is organized that determines how it will behave," explained Clark L. Hull, professor of psychology at Yale University, when I asked for simple analogies to make clear this point of view. "If material is organized in a certain way, it will fly like an eagle; if it is organized in another way, it will fly like an airplane. There was a time when the property of aerial locomotion was associated only with organic life. Suppose there had been a system of philosophy which asserted that aerial locomotion must necessarily be associated with a mysterious something called life? Such an attitude is comparable to that of the vitalist who holds that it is impossible for a thing to think unless it is alive. Leonardo da Vinci doubted the first supposition; the Wright brothers also doubted it—and today airplanes fly automatically under the control of gyroscopic mechanisms. Equally, some of us doubt the second supposition. In experimental support of our doubt we can point to certain man-made machines which reproduce some of the rudimentary behavior of the conditioned reflex."

2

Several years ago Dr. Hull was conducting a seminar in psychology. The class met in the evening, a group of graduate students for the most part, and discussion was lively, ranging the frontiers of psychological thought. For several sessions the seminar had been considering the conditioned-reflex experiments, and one evening, as the discussion closed, Dr. Hull gave his class a jolt. "If the mechanistic theory is true it should be demonstrable," he proposed. "One week from tonight I want each of you to bring in a model which will display the characteristic behavior of the conditioned reflex."

He said that as a gesture more than anything else, in an effort to stimulate the students to think concretely on the subject. But the following Wednesday three models were brought to class, and all of them worked. Two were rather crude arrangements of wooden levers, but one was fairly ingenious—the design of a young physiological chemist who had come to the seminar to please his wife. She was a member and had persuaded her husband to attend. "Perhaps our theoretical speculations bored him," remarked the professor, "but my suggestion that a model might be made to test the theory appealed to his scientific imagination, and he worked the thing out on the basis of electrochemical principles."

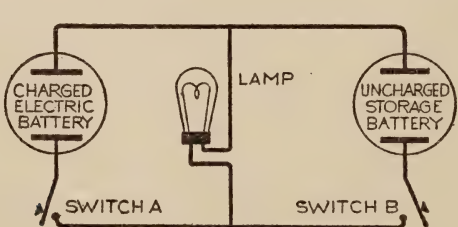
This guest of the seminar was H. D. Baernstein. A search through the psychological journals shows that several earlier trials in the field of simulating mental processes had been published, but Baernstein was not aware of them. And as his model is the first of a series of several originating from this chance suggestion, we may regard it as a landmark. Some newspaperman heard of it and published a story describing the thing as a mysterious mechanical brain. The news item, picked up and reprinted by others, went over the country, and resulted in a number of letters of inquiry. The Baernstein device was publicly exhibited for the first time in May, 1929, at the meeting of the Midwest Psychological Association in Urbana, Illinois.

What the psychologists saw was an arrangement of wires, batteries, glass tubes, heat coils, two electrical switches, and a small incandescent lamp—all mounted on a flat wooden base. It was explained that the two switches represented two different stimuli in an analogue of Pavlov's conditioned-reflex experiment, while the lamp was intended to provide the response.

The demonstration was simple. First, push switch *A*. The lamp instantly glows—a behavior corresponding to the mouth-watering of Pavlov's dog at the sight of food. Ap-

parently there is a direct connection between switch *A* and the battery which energizes the lamp. If you push switch *B*, however, the lamp does not glow. Its inaction corresponds to the dog's indifference to the ringing of the bell. You assume that switch *B* has no connection with the battery and the lamp. But now close both switches, and hold them down for several seconds. After a few of these simultaneous closings, you abandon switch *A*. You press switch *B* alone—and the lamp glows! Press it again and again; it lights up repeatedly—just as the dog's mouth waters repeatedly at the sound of the conditioned bell. Switch *B* has become "conditioned" to switch *A*, for the lamp now will respond to either stimulus. But if you keep pressing *B* alone for several trials, there comes a time when the lamp does not light. The conditioned reflex has suffered what Pavlov calls "experimental extinction." However, a few moments of repeated conditioning will restore the tendency, and thereafter the machine will recognize and respond to its conditioned stimulus quite as persistently as the dog reacts to his dinner bell.

As a preliminary to the explanation of Baernstein's mechanism, let us consider first a simpler type of thinking machine which was designed later by another of Dr. Hull's students, R. G. Krueger. Krueger was a young electrical engineer before he took up psychological studies, and he seized on the storage battery (or polarizable cell, as it is also called) as the key to his conditioning apparatus. The arrangement which he set up may be diagrammed as follows:



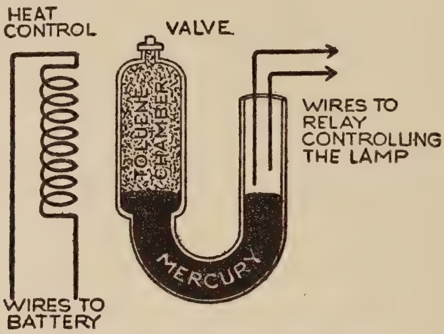
Simple type of thinking machine

The hookup is simple. When switch *A* is closed, the entire left half of the diagram becomes a closed circuit; the current from the charged battery flows through the lamp and causes it to glow. Similarly, when switch *B* is closed, the entire right half of the diagram becomes a closed circuit with the lamp; but there is no energy in the uncharged storage battery; therefore the lamp gives no response. When both switches are closed simultaneously, the current from the charged battery not only flows through the lamp, but it also flows through the uncharged cell, and some of its energy is stored there. Thus the process of conditioning consists of charging the storage cell, and after this is accomplished Switch *B* alone can invoke the light. Prolonged pressing of *B* will exhaust the stored energy, thus accounting for the "experimental extinction." But if you leave the exhausted cell passive a few minutes a certain chemical readjustment will take place, a "spontaneous recovery" such that if you now press switch *B* the lamp will glow feebly—a mechanical analogue of memory.

Krueger's working model included not only the conditioned stimulus represented by switch *B*, but a whole series of them. Thus, after conditioning *B* to *A*, it was possible to condition a new circuit *C* to *B*, and after that a circuit *D* to *C*, and so on for a considerable sequence. This provided a chain of reactions comparable to those of Pavlov's experiments in which, after conditioning the sound of the bell to the showing of the food, Pavlov conditioned a flash of light to the sound of the bell, and then the sight of a luminous disk to the flash of light, and so on. The heart of the Krueger model is the uncharged storage cell with its capacity for accumulating energy (a process analogous to learning), and its capacity for exhausting its energy (experimental extinction), and its capacity for spontaneous recovery (remembering).

The Baernstein model is more complicated, but the distinguishing feature of its mechanism may be described as a

valve actuated by heat control. The essential features of this are sketched in cross section as indicated.



Control valve of thinking machine

The valve is in the *B* circuit, and, since the circuit is open until the two wires in the right arm of the valve are connected, the mere pressing of switch *B* will have no effect on the lamp. But when both *A* and *B* switches are pressed, the connection thus made allows current from the battery to pass through the heat coil shown to the left of the valve. (In the apparatus, the heat coil surrounds the toluene chamber.) As the coil gets warm, its rising temperature heats the toluene. This toluene is a liquid which expands rapidly with a moderate rise of temperature. As it expands, the toluene forces the mercury down into the U-tube. The mercury rises in the right arm of the tube until finally it touches the ends of the two wires in that tube, and thus makes contact between them. Thereafter switch *B*, through this mercury connection, is able to send a current from the battery to the lamp. But after a while the toluene cools and contracts, the mercury assumes its old level, and the connection between the two wires is broken. Then we may say that the machine has forgotten.

These two mechanical-electrical arrangements—each quite different and yet both alike in that each provides its apparatus with a means of changing its internal setup in

response to an outside stimulus—furnish a clue to the understanding of all thinking machines. In each of them there is some provision—like the polarizable cell of Krueger's model or the thermostatic control valve of Baernstein's model—a provision for adjusting the mechanism to what it experiences, or, as the objective psychologist bluntly puts it, for learning.

Learning is interpreted as an effect of a trial-and-error process. In 1934 Dr. Hull published a paper in one of the technical journals in which he set forth in detail a theory of the animal mechanism of trial-and-error learning. A student at Miami University in Ohio, D. C. Ellson, chanced to read this treatise and it inspired him to try to reproduce the theoretical system in a mechanical model. He set up a series of three electromagnets in circular arrangement, and suspended an iron bar so that it was equally distant from all. The magnets were of different degrees of strength: one measured 100 magnetic units, another 70, the third, 30. The strength of these electromagnets in each case was determined by the number of electrically active turns of wire surrounding its core. And there were internal switches providing for the automatic cutting out of a certain number of turns, thus reducing the magnetic strength, or, alternatively, for the cutting in of a certain number of turns, thus increasing the magnetic strength.

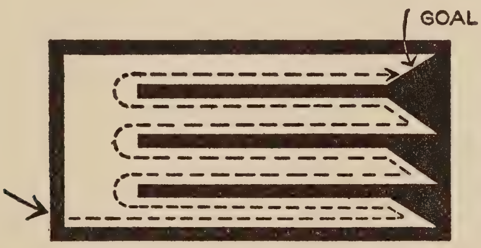
Suppose you wish to teach the iron pendulum to move to a certain magnet, to the weakest magnet, *Z*. You set a certain relay to indicate this goal, and close the electrical circuit which actuates the mechanism. The pendulum, under the pull of magnetism, moves first to the strongest, which is magnet *X*. But that is not the choice you have indicated as the goal, and the mechanism is so set that when the pendulum reaches the point of contact with magnet *X*, the electrical connection for that magnet is switched and automatically 30 of its 100 turns of wire are cut out. Its strength is reduced by 30 per cent, and in the tug of

war among the magnets *Y* now assumes the control. The pendulum moves to *Y*. But as *Y* is not the goal called for by the setup, the same automatic process occurs here: certain coils of the wire surrounding the *Y* core are shunted out, leaving the dominance to magnet *Z*. The pendulum immediately moves to *Z*, and, as this is the goal, a reward in the form of increased induction is given—for one must use rewards to teach magnets and pendulums as well as dogs. What happens is that the contact at *Z* causes a switch to close, and this cuts in additional turns of wire, thus insuring that on the next trial *Z* will be stronger than it was. *X* and *Y* are weaker now, and *Z* is stronger; but *X* is still the strongest, and *Y* is next in strength. On the second trial the pendulum again moves first to *X*, then to *Y*, and finally to *Z*—but this time it performs the sequence more rapidly. It is learning. At the end of the second trial, additional turns of the wire have been cut out of *X* and *Y*, and, correspondingly, additional turns have been cut in to *Z*. Eventually, after five trials, the pendulum wastes no time in experimenting. Magnet *Z* is now the strongest, and the iron bar proceeds directly to its goal. It has learned by trial-and-error behavior. Nor is the machine standardized to *Z*; the goal may be set as *Y* or *X* according to the will of the operator. The machine can be taught to move to either of them by the same process.

Still another episode in this narrative has its setting in the Pacific Northwest. It seems that the newspaper account of Baernstein's model of 1928 caught the attention of a young man in the state of Washington, Thomas Ross. Ross had been working on an idea for an automatic typewriter, thought that the thinking machine might suggest some useful features for his invention, and so he wrote for particulars. Dr. Hull answered the letter and the boy came back with another. Thinking machines interested him: he thought he would make one himself. Eventually there arrived in New Haven, by express from the remote North-

western village, a carefully crated package. It was Ross's thinking machine: a device of springs, levers, pinions, electromagnets, a protruding arm (like the boom of a toy derrick), and a vertical "maze" (a series of metal shelves suggesting a miniature cupboard). Odd scraps of material had gone into its making—whatever was available—but the thing is said to have worked.

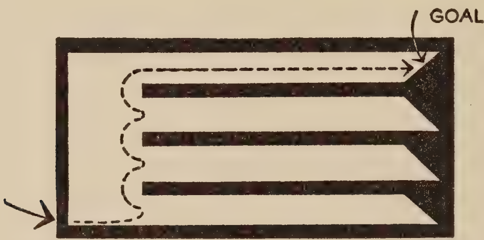
Set the tip of the protruding arm at the entrance to the bottom passage of the maze, and start the machine operating. The tip pushes along the passage until it comes to the dead end. It can go no farther, and the pressure of the dead end actuates a switch in its mechanism which causes it to reverse. It retraces its steps, and moves upward to the entrance of the second passage. Here the exploratory process is repeated: the arm moves along the second passage until the blind alley's closed end on the right stops it, actuates a switch as before, and so causes it to reverse and retrace its way out of the second passage just as it did out of the first. By a similar procedure, it explores the third passage. In this way, by trying every path, it comes at last to the end of the maze and so to the goal. The course of its journey through the maze is indicated by the dotted line:



Maze of learning machine. Starting from left is the path traversed by the arm of the machine in first reaching the goal.

It would require a complicated array of diagrams to picture the various circuits, switches, electromagnets, and other essential parts of the mechanism which drives and

controls the movement of the protruding arm along this path through the maze. The machine is electrically driven, and the tip of the arm carries metal points which make contacts with the metal slots of the maze and communicate an electrical current. As this electrically sensitive tip travels the circuitous route outlined by the dotted path, and experiences the blind alleys, these encounters cause certain switches in the actuating mechanism to be changed. The switches cut out certain circuits and cut in other circuits, as a result of which the arm is held to a more direct route on its second journey through the maze. This shorter path of the machine, after the conditioning, can be made clear by revising the dotted path in our diagram, thus:



After the machine has learned. Its path to the goal now is more direct.

With further refinement of mechanism, says the inventor, it would be possible so to condition the machine that it would proceed by the shortest possible path, *i.e.*, vertically upward in a straight line from the starting point to the opening of the upper passage, and then horizontally to the right to the goal.

Since this early experience Ross has proceeded to college, and during the last three years has been working in psychological research under Dr. Stevenson Smith at the University of Washington in Seattle. For several years Dr. Smith had had in mind an idea for a maze-learning machine which would travel a track, and now he put Ross to work on the job. Within a few months they had made

and were able to demonstrate a mechanism which newspaper writers promptly named "the robot rat."

Rats are favorite subjects for the experimental psychologist, and are particularly apt at learning the twists and turns and obstacles of mazes. So too with the Smith-Ross device. It might be mistaken for a toy electric locomotive: a vehicle a little more than a foot long and about seven inches wide, loaded with motor, solenoids, gears: all the equipment necessary for actuating and directing its movements. The mechanical rat travels a grooved track from which fork off at irregular intervals twelve open sidetracks leading to dead ends. These are equivalent to the blind alleys which the living rats encounter in their maze running. When the mechanical rat takes a siding and bangs into the dead end, a switch is turned within its mechanism which causes the motor to reverse; so the machine backs up, gets onto the main track again, and then moves forward, this time passing the fork. It has learned to avoid the useless turn. And so with each fork; the machine bumps and learns. The significant detail is that this process of conditioning alters arrangements only *within* the mechanical rat—nothing is changed in the track. The environment remains unaltered; but after it has experienced the environment the machine has been so conditioned and trained by this environment that it will travel the track from beginning to end without making a false turn.

"It remembers what it has learned far better than any man or animal," said Dr. Smith. "No living organism can be depended on to make no errors of this type after only one trial."

But how does it learn, and how remember? The thing is electrically activated, propelled by a motor, and its choice of route is determined by a rudder wheel which travels the grooved track. Before learning, the machine is set so that this rudder wheel will follow the right-hand branch of every fork. Every time it takes a side-track and bangs into a

dead end, not only is the motor automatically reversed, but one flange in the edge of a twelve-flanged "memory disk" is depressed. The depression of this flange allows a rocker arm to fall into a hole, the dislocation of the rocker arm causes an electrical contact to be made and another contact to be broken, thus connecting one solenoid and disconnecting the opposite solenoid. It is these solenoids that, by their magnetic influence, steer the machine. They pull to one side or the other a lever which controls the rudder wheel, and after the first collision the flange is so depressed that thereafter the rudder wheel must take the lefthand branch of that particular fork. In passing the next section of the track, two levers in the machine brush against stationary outside posts and cause the memory disk to turn forward one division. But here at this new division of the disk the flange is still upright, and the effect of its being turned forward is to lift the rocker arm back to original position and again set the rudder wheel for a right turn at the next fork. In this way, as it moves through the maze, always turning right at the first trial, the record of its collisions with dead ends is indelibly written into the memory disk. If in any instance the right-hand turn proves to be the main-line path, the machine will encounter no collision and, therefore, will not alter the flange and the position of the rocker arm in that twelfth of the memory disk. After the machine has traversed the twelve sections of the maze the memory disk will have revolved to the original starting point. But it is so marked by the experiences of its first journey that thereafter it infallibly guides the rudder wheel past all false turns. The living rat learns by experimenting—that is, by experiencing—and so does the machine.

3

The skeptical bystander, watching a demonstration of one of these arrangements, is not fooled. "Truly an ingenious machine," he may remark, "but *not* a rat."

The psychologist agrees. The apparatus has been designed to simulate only one kind of rat behavior—the behavior of learning the most direct route through a maze.

"But your robot blindly bangs into obstacles, and by these collisions sets prearranged switches in its electrical control system which thereafter turn its wheels in prearranged ways, and by mechanical direction steer clear of the sidetracks," persists the amateur critic. "That is not thinking—that is merely turning switches and resetting relays."

It is *merely* turning switches and resetting relays, agrees the behaviorist, but how do you know that learning and thinking are not the same thing essentially? All we see of the living rat's procedure is that it follows blind alleys at first, collides with dead ends, retraces its steps, and eventually, after a series of experiences, it makes the trip through the maze without repeating these mishaps. If it is behavior that we are judging, and if our study is confined to "observables," where is the difference, in principle, between what the machine does and what the rat does?

Admittedly the maze-running machine is not a rat, just as the airplane is not an eagle. It is only an analogue capable of simulating one limited type of rat behavior. And so with other models. The glowing of the incandescent lamp in Baernstein's model is not the same operation as the dripping of saliva from the mouth of Pavlov's dog, but the functional relationships between stimulus and response in the dog are of the same order as the sequence which conditions the lamp response. It is possible that a model might be built which would actually salivate at the sound of a bell, but so complicated a construction is not necessary to provide a test for the psychologist's theory. And that, we remember, is the practical justification of model building: to test theory. If a mechanical artifact can be made to reproduce the conditions of the theory—no matter how crude or elementary the reproduction—evidence is thereby adduced for the reasonableness of the theory.

"But we are not deceiving ourselves," said Dr. Hull. "The model provides a test for the internal logic of our theory, but it does not absolutely prove the truth of the theory. If we have a mechanical hypothesis of thinking, and if we build a mechanical model following this hypothesis, and if our model executes behavior of a kind analogous to that which in the living animal we call mental behavior, then we can fairly claim that a machine can think—though we may be sure that the living organism is not the same kind of machine. Thus models check the reasonableness, though they cannot prove the truth, of the theory."

The construction of model psychic mechanisms is a fascinating diversion; perhaps some would call it a weakness to be indulged only occasionally. For the most part the psychologists study the living organism itself. In his laboratory Dr. Hull has under way a huge program of research with living material. The theory of the conditioned reflex is being investigated and tested here through experiments on the habits of men as well as on those of white rats, dogs, and monkeys. Already a large body of data has been gathered, and it has considerable significance in practical life—but this subject matter is too voluminous to be introduced incidentally here.

Hull has never made a model. Stevenson Smith waited for a young prodigy at mechanism to come along before he undertook to materialize his idea of the mechanical rat. Most of the thinking machines have been built by students, many of them by engineering students. At the Massachusetts Institute of Technology a young electrical engineer, N. B. Krim, devoted his graduation thesis (by which he completed his qualifications for the engineering degree in 1934) to an exposition of thinking machines. He made a simple working model. And in his thesis, Krim provided blueprints for fourteen different electrical circuits, each designed to reproduce adaptive behavior, some of them promising responses of a high degree of complexity.

A conclusion one derives from observing these machines is the amount of mechanism needed to provide even the most elementary behavior. The mechanical rat is equipped to learn a maze, and its thinking stops there. But a living rat is equipped to learn hundreds of different tasks. "To make a model which would reproduce all the behavior of a rat would require a mechanism probably as large as the Capitol at Washington," said Dr. Hull. To make a model which would discriminate among the various symbolical meanings of the color red, and respond to the emotional patterns characteristic of human responses to this symbol, would require a far larger array of mechanism. What would it take to reproduce the whole behavior of a man— of an average, typical ordinary man-in-the-street? On the same scale such a machine might occupy a whole county or spread over an entire state, so intricate and almost infinite in number are the cross connections, the associations, represented by ordinary human behavior.

In a preceding chapter I have discussed the mathematical approach to biology which has been undertaken by Nicolas Rashevsky, and suggested the nature of his models of the living cell. Dr. Rashevsky has not confined his method to elementary processes of primitive life. He has published the general specifications for a machine which he claims will exhibit "purpose," and in particular will "tell a lie" which "may be described as purposeful." The actual construction of the machine has not been attempted. It "will be a matter of tremendous expense and labor," Dr. Rashevsky admits, but of its possibility he has not the slightest doubt. Anyone who has the inclination, the mathematical acumen, and the necessary where-withal, will find all clues freely revealed in Rashevsky's paper in the *Journal of General Psychology* (1931).

Questions of biological mechanism came up for discussion at a meeting of the American Philosophical Society held at Philadelphia a few years ago. After hearing various argu-

ments on both sides, Dr. Cyrus Adler threw out this challenge:

"If the mechanistic theory were carried to the extreme and there were produced, as I understand there can be produced in the laboratory, a robot that could in every way duplicate the acts of what we call man, it has been suggested, and I regret that I cannot take credit for this suggestion, that the acid test as to the identicalness of the real man and the mechanistic man is whether the latter would ever engage in the search after truth."

Would the machine ever develop a curiosity as to its nature, its origin, its destiny?

What say the psychologists, the biochemists, the biophysicists, the modelmakers? "Stands Scotland where it did?"

Chapter XV · CHEMISTRY AND THINKING

> The cells of a human brain continue to act because the blood stream brings to them chemical free energy in the form of sugar and oxygen. Stop the stream for a second and consciousness vanishes. Without that sugar and oxygen there could be no thought, no sweet sonnets of Shakespeare, no joy, and no sorrow.
>
> —F. G. DONNAN, THE MYSTERY OF LIFE

WHATEVER we may infer from nonliving mechanical analogues as to the nature of the mind, its close physical relationship to the brain is everywhere confirmed. And the direct dependence of the brain upon the chemical interchanges of the body is equally a matter of universal observation. It is not only that substances foreign to the body, such as a few drops of alcohol, a few whiffs of an anesthetic, or microscopic granules of a narcotic, may profoundly affect the organ of mind, but that the health and very life of the organ depends from moment to moment, as indeed does that of every organ, upon the ceaseless flow of the blood stream and the constancy of its cargo of nutrients. The brain appears to be peculiarly sensitive to the physicochemical equilibrium. When that equilibrium is upset the brain and its nervous system are the first to feel the shock. In experiments with dogs at the Rockefeller Institute it was found that if circulation were interrupted only 5 minutes, the dogs were easily resuscitated to appar-

ently normal condition; if the interruption lasted 8 minutes, the dogs were resuscitated but with impaired intelligence; if the interruption of blood flow were as long as 10 minutes, resuscitation was difficult and when accomplished the dog was blind and paralyzed and in other ways gave evidence of serious brain injury. When death comes to the body, the brain is the organ that dies first.

Is it possible to gauge, not only the brain's living, but also its thinking and other mental functioning, by the nature and rate of the body's chemical interchanges? There is, quite obviously, a chemistry of living. Is there also a chemistry of thinking?

I

A person lying in bed in the early morning before breakfast, having taken no food since the previous night's dinner, awake and yet in a state of repose, his muscles lax, his mind at ease, is a thermodynamic machine at or near its lowest ebb of activity. Just to keep the heart beating, the lungs pulsing, the other organs in tone and functioning, requires a certain minimum of energy. This energy is continuously supplied by a chemical reaction or series of reactions in which some of the fuel taken in as food is combined with the oxygen breathed in as air. By this process, literally a burning, heat is generated and energy is made available. Individuals differ as to their needs, but on the average the requirement for an adult is about 1 calorie a minute, 60 calories an hour—an energy rate equivalent to that represented by the combustion of two lumps of sugar in an hour.

This energy level is basic. It measures the cost of merely keeping alive. Any increase in bodily activity calls instantly for an increased burning of fuel. Merely sitting up raises the energy requirement by about 5 per cent; standing, by about 10 per cent; and walking briskly may at once treble the need, and speed the calorie output by 200 per cent.

The energy requirements of the body in repose and in action have been the subject of prolonged study at the Nutrition Laboratory in Boston, one of the research centers of the Carnegie Institution of Washington. Here Francis G. Benedict and his colleagues have measured the metabolism of man and other animals under a variety of conditions, seeking always to find a correlation between such measurables as oxygen consumption, carbon dioxide output, heat production, and the activity of the organism. An airtight, heat-tight room was constructed at the laboratory, so arranged that several persons may live in it for days without discomfort and carry on all the ordinary activities of eating, sleeping, working, playing, while sensitive apparatus measures their intake of air, their output of waste, the heat generated by their living processes. Dr. Benedict found that the intake of oxygen is a precise index to all the other factors, so his later studies have centered on this single indicator. He has devised an airtight helmet and other portable apparatus for measuring oxygen consumption, and with this has been able to go into the field and measure the metabolism of elderly persons in their homes, of workmen at the bench, of women at the ironing board, and by such means has accumulated a wide range of data on the energy requirements of the human machine at work and at play.

He finds that a person engaged in a sedentary occupation, a desk worker, for example, requires about 2500 calories daily to supply basal needs and provide the energy necessary to sustain his work. For manual workers the needs are greater. A farmer requires on the average about 3500 calories daily, while a lumberman, engaged in the more laborious tasks of sawing, chopping, and lifting logs, uses about 7000 calories. A professional bicycle racer, who obligingly submitted to the scientists' measuring device, developed the enormous requirement of 10,000 calories—approximately four times the rate of the desk worker.

I cite these representative cases out of thousands of measurements that have been made. The evidence is completely consistent in showing that the more active a person is physically, the higher is his rate of oxygen intake, the greater is the combustion of fuel in his cells, and the larger is his output of energy. Every lifting of an arm, every speaking of a syllable, every quiver of an eyelid, costs energy which must be supplied by the burning of an additional portion of fuel.

If physical activity demands its toll and shows its costs so unmistakably in the increased chemical activity of the body, what of mental activity? Who that ever solved a tough problem in mathematics, or worked through a 3-hour examination at school, or participated in an extended conference calling for close attention to many details and the decision to act in a critical situation, can forget the feeling of fatigue which follows these mental exercises? Surely the labor of the brain is no less exhausting than the labor of the muscles.

Since this is abundantly affirmed by experience, we may ask, what are the energy requirements of mental effort? If a sedentary desk worker who is engaged in routine duties requires 2500 calories daily, how many additional calories are needed when that same desk worker has to apply his brain to a knotty problem?

Such questions led Dr. Benedict to a searching experiment.

2

The physiologist was aided in this study by his wife, Cornelia Golay Benedict, his collaborator in many previous studies. They selected as subjects one woman and six men. The woman had been a professional accountant, five of the men were university trained, and two were of professorial rank. Presumably each was capable of sustained intellectual effort. All were in good health.

The experiments were carried forward during a series of forenoons, the subjects arriving at the laboratory at about 8:30 without breakfast. The instant food is taken into the body the rate of chemical activity rises automatically, since energy is required for digestion. Therefore, to avoid this complication, the seven willingly fasted each day until about noon. During the 3 or 4 hours each wore the helmet continuously, though the actual testings of the effect of mental effort were limited to periods of 15 minutes and were relieved by periods of rest.

For each day the program was about as follows. The subject was seated comfortably, in a position involving the minimum of muscular tension or strain, a posture that was maintained so far as possible throughout the series of measurements. The idea was to obviate extra energy demands due to physical requirements. In this early stage of relaxation and mental repose, the metabolism was measured. That gave a sort of base level with which to compare changes. Then the subject was called to a state of mental attention, and again the metabolism was measured. Finally, the person was told to solve a mathematical problem, and during this intellectual activity the metabolism was measured. Usually the problem was to multiply a two-digit number by another two-digit number. For example, what is the product of 37 multiplied by 29?

No paper and pencil were provided, for the use of writing materials would call finger muscles into play, and physical effort would be added to mental effort, thus confounding the result. No, the whole computation must be carried on in the head. And when the problem was solved, the answer must not be announced orally. Speaking would bring into action the muscles of the vocal organs and add their toll on energy. So the subject was asked merely to touch a sensitive electric switch which lay at hand and thereby signal the conclusion of the problem, whereupon the ex-

perimenter would take the signaler's word for it that the problem was solved, and would propound another.

After a morning of these mental gymnastics, there was not a one of the seven who did not feel fagged. Each was glad of the opportunity for a change, oppressed by a sense of exhaustion, and inclined to believe that sawing wood or sweeping floors might be preferable to three hours of sustained mental labor.

There was no question about the *feelings* of the subjects of the experiment. The thinking did take something out of them. But what about the *records* of the unemotional instruments—the measuring devices which unerringly write down the rises and falls of the body's chemisms?

Surprisingly, the measurements showed scarcely any difference between the energy requirements of the body in mental repose and those of the body in mental activity. The rise in oxygen consumption for the latter was only a trifling 3 or 4 per cent.

There were also slight increases in the rates of heart beat and respiration and in the ventilation of the lungs, changes which require a corresponding acceleration in muscular activity; and, according to the Benedicts' interpretation, these increases in the activity of heart and lung muscles might well account for the increased use of oxygen. Even if the entire 4 per cent increase be attributed to the extra demands of the thinking brain, the toll is amazingly slight—approximately 4 calories an hour, an amount of energy equivalent to that supplied by eating half a peanut!

But the energy released by the combustion of half a peanut may be relatively enormous if we consider the small proportion of body material involved in the thinking process. This was emphasized by the Viennese physiologist Arnold Durig in a communication to Dr. Benedict. Professor Durig estimates that the number of brain cells which function in an act of mental effort can weigh hardly more than 7 grams (¼ ounce)—proportionately about one-hun-

dredth part of 1 per cent of the average human body weight. For this small mass of cells to be responsible for the 4 per cent increase in body metabolism which the Benedicts detected, it would be necessary for the brain cells to have a metabolic activity four hundred times greater than that of the average body cell, says Durig. Metabolism *for* mental effort is one thing; metabolism *due to* mental effort is quite another.

We may say with confidence that there is a metabolism necessary for mental effort, because, to repeat the idea with which this chapter began, any interference with the stream of blood which continually pulses to the brain, any tampering with its freights of oxygen, sugar, and other essentials, is quickly reflected in mental infirmities. In his Terry lectures at Yale, Sir Joseph Barcroft told of some rather drastic experiments that he performed upon himself in pursuit of this problem. In one test he spent 20 minutes in a sealed room whose air was diluted with more than 7 per cent carbon dioxide gas. This meant that he was breathing and putting into his blood more carbon dioxide than is normal. The effects showed in symptoms of mental fatigue: "An inability to concentrate on or even listen to conversation without effort; the tendency to take up a newspaper, read a few lines of one paragraph, preferably something quite unimportant, then a few lines of another, without finishing anything." This inability to concentrate—and Sir Joseph points out that it was an impairment of the higher qualities of the brain—lasted about two days. In another experiment he spent only 5 minutes in air containing the higher mixture of 10 per cent carbon dioxide, and "when I came out I was retaining my grip on things only with an effort."

From many experiences and observations Barcroft concludes: "The thoughts of the human mind, its power to solve differential equations, or to appreciate exquisite music, involve some physical or chemical pattern which

would be blurred in a milieu itself undergoing violent disturbances."

3

This physical or chemical pattern also displays electrical properties. Certain areas of the brain are undergoing continual changes in electrical potential, and the resulting differences in potential between one area and another give rise to minute electrical currents. Recently it has been found possible to cause these microcurrents to write their records of pulsations. The result is the attainment of a new index to the ceaseless energy flux of the organ of mind, the so-called "brain waves."

The existence of electrical activity in the brains of animals has been known since 1875, but systematic study of the effect in man dates only from 1929. In the latter year the neurologist Hans Berger, at the University of Jena, borrowing a device from the radio engineer, attached wires from opposite sides of a man's skull to a powerful vacuum-tube amplifier. The delicate currents from the brain were thereby stepped up, magnified by a factor of millions, and when led off into an oscillograph they showed a wavelike pattern. Among this pattern Berger discovered a certain predominant rhythm with a vibratory frequency of about 10 a second, and these pulsations he called "alpha waves." There was another rhythm, less pronounced but often detectable, which was of shorter wave length and higher frequency, and these he named "beta waves." Later investigators have identified other pulsations of irregular wave length and uncertain rhythm.

The pattern of waves, if pattern there be, is complex and of a language difficult to decode. But the fact that at last man has an instrument which can pick up and respond to the delicate activities of the thinking mechanism is of the greatest encouragement. Today brain waves are the subject of study in a dozen leading laboratories of Europe

and America. Important advances in this new field have been made by E. D. Adrian at Cambridge University; by M. H. Fischer and A. E. Kornmueller at Berlin. In the United States, Brown University, Harvard, and the Loomis Laboratory among others have contributed valuable studies.

The waves which are recorded from outside the skull seem to originate in the cerebral cortex, that ensheathing bark of gray matter in which reason and creative thinking have their home.

"It has required upward of twenty million years of evolutionary history to fabricate the architecture of this cortex out of the simpler nervous structure of the brain stem," points out C. Judson Herrick, psychologist at the University of Chicago. "The larger outlines of this history can be read, yet we are still profoundly ignorant of how it performs its miracles of production that we know it does produce. But these mysteries are not insoluble, and the last quarter century has contributed more toward the solution of the problem—how the brain thinks—than all the preceding centuries of scientific research yielded. We have new instruments—oscillographs with radio-tube amplifiers—and new points of view that promise as great a revolution in the physiology of the nervous system as the invention of the microscope effected in the field of anatomy."

The microscope can work best with restricted things, small colonies of tissue or individual cells, and often the material has to be stained, that is to say, injured and even killed, for its details to become visible through the lens. But the electroencephalograph (as the technicians call the brain-wave detecting and recording apparatus) has no such limitations. It works with the whole organ, the living brain in place, and without interfering with its normal functioning. It is not even necessary to puncture the skin. Present-day instruments are so sensitive that two metal electrodes in contact with two different areas of the scalp will pick up

the flow of electricity passing from a brain area of high potential to one of lower, and this can be done without discomfort or annoyance to the person submitting himself to the experiment. Indeed, any discomfort or annoyance will be reflected in the pattern of waves; therefore it is important that the subject be at ease and without apprehension. At the Harvard Medical School a small cubicle has been paneled off at one side of the laboratory; it has been fitted with a couch on which the subject lies during the experiment; and frequently one or two preliminary periods are run in advance of the actual test as a means of making the apparatus and procedure familiar, thereby relieving anxiety. Once confidence is established, the comfort of the couch and the warmth and peace and twilight of the closed room have a soporific effect, and in many experiments it has been a problem to keep the person awake. This is necessary, for the wave patterns during sleep are different from those during wakefulness, while those of the awake but passive brain with eyes closed are different from those of the seeing brain or the thinking brain.

These effects were easily demonstrated. The subject reclined at ease in the closed cubicle, the two electrodes adjusted to his head and connected with wires. The wires led outside through a series of amplifiers to a tiny electromagnet which actuated a pen on a moving strip of paper, a tape not unlike the ticker tape of Wall Street. The man on the couch inside had been instructed to "keep your eyes closed until we tell you to open them, and just take it easy." As soon as the switch was pressed, completing the circuit, the pen began to write a wavy line. The waves were fairly regular, and came about ten a second—a record of alpha waves.

"Keep your eyes closed, and multiply eighteen by eleven."

Immediately the pen changed its antics. The bold leisurely strokes ceased, and in their place came a series of

smaller waves, some barely perceptible. Apparently the mobilizing of mental faculties from idleness to work had affected the currents which our apparatus was able to pick up, and now the pulsations were feebler. This period of smaller waves lasted several seconds, but after a while the waves began to lengthen and the pen grew bold again, writing out the oscillations of the alpha rhythm. The experimenter knew then that the brain had solved the problem and was relaxed once more. But the relaxation was temporary, for in another instant the pen resumed the narrow less-defined strokes, as though the brain were returning to its task. And so it was; for, as the subject later explained, after multiplying the numbers and getting an answer, he was disquieted by the thought that it was a wrong answer. Accordingly he repeated the multiplication to a satisfying conclusion. After that, more alpha waves.

There are other means than mental arithmetic for smoothing or suppressing this ground swell of alpha waves, as our experimenter now demonstrated.

"Don't open your eyes," he warned.

The alpha rhythm ceased. The effect of this call to attention was very transitory, however, for presently the alpha waves resumed.

"Now open your eyes," and at the command the experimenter turned an electric switch which lighted a lamp on the wall inside.

Quickly the alpha pattern changed, reverting again to the weaker pattern. And the new pulsations persisted for some time, demonstrating that the act of seeing has a profound effect on the electrical output of the brain.

The experiments cited are typical, and their results correspond to those obtained in many other laboratories, though it must be said that there are wide variations in the responses of different individuals. A few persons among those tested show no alpha rhythm. Some show irregular patterns, large waves interspersed with small. But many

give a fairly recognizable rhythm, though the wave length varies slightly from individual to individual.

In general we may summarize findings thus: Those persons whose brain potentials characteristically reveal an alpha rhythm, cease to show it (1) when the brain is employed in conscious mental effort, or (2) when the brain is called to attention, or (3) when the eyes are opened in a lighted room. By other experiments it has been shown that alpha waves are more pronounced when one of the electrodes is placed at the back of the skull over the visual area of the cerebral cortex, the brain region which is receptive to messages from the optic nerve. In some way, we do not know why, alpha waves are related to the sense of sight.

4

Results so far described refer to experiments with the subject awake. Interesting variations show when the machine is set to record the currents given by a sleeping brain. This is a project that has engaged the interest of Alfred L. Loomis, E. Newton Harvey, and Garret Hobart at the Loomis Laboratory in Tuxedo Park, New York. Here a bedroom has been equipped with special apparatus to insure controllable conditions. The room is electrically screened to guard against stray currents from the outside; it is equipped with a sensitive microphone to record all noises heard within the room, and with a photoelectric device to record the movements of the bed in response to the sleeper's restlessness. Sleep records from many different persons, ranging in age from 11 days to 75 years, have been taken while a device ceaselessly wrote the history of the brain's electrical rhythms. Finding that in a night the customary apparatus would turn out half a mile of paper tape, the Tuxedo Park investigators constructed a revolving drum 8 feet long on whose paper surface the pen may write an entire night's waves in an advancing spiral. Moreover, they devised an arrangement by which three circuits of

electrodes are used at the same time, and three pens simultaneously record the waves from three pairs of opposing areas on the same head. Records of every heartbeat, every pulsation of the lungs, every movement of the body, are also inscribed. These several messages travel electrically through shielded cables to the control room 66 feet away, and there are entered by automatic pens in different colored inks on the spacious paper of the revolving drum.

The purpose of these accessory hookups is to determine whether or not there is any correlation between brain waves and the rates of heartbeat, respiration, and other muscular movements. The investigators found no synchronism with heartbeat and none necessarily with respiration, though at times a definite change in the wave occurs with each breath. Regular snoring shows no correlation, but an occasional isolated snort may start a series of alpha waves.

The Tuxedo Park experiments show three types of waves to be characteristic of sleep. First are the "trains" of alpha waves (10 a second) which appear in the first stage of falling asleep and reappear during light sleep. Second are the "spindles," short bursts of waves of rapidly increasing and then rapidly decreasing amplitude, with a frequency of 14 a second. Finally, there are irregular waves which Loomis, Harvey, and Hobart call "random."

In general, spindles and random waves are associated with deep sleep, and the trains occur during interrupted or light sleep. Often a sudden change from the random type to regular trains resulted from merely speaking to the sleeper. Interestingly, too, noises of an accustomed nature, such as the honking of an automobile horn, frequently have no effect, while anything that indicates the presence of another person may cause spindles and random waves to give place abruptly to trains. A cough, a whisper, a faint footfall, the rustling of paper—these slight noises have in many cases produced sudden trains of alpha waves, when loud noises and bright lights brought no response from a

sleeper. "We are inclined to believe that the starting of trains by sound is not a direct result of the sound stimulus, but is connected with a change in the normal level of brain activity," report Loomis and his associates.

When brain waves are being received from two different areas of the head, from a back area and a front area, for example, each may send pulsations of a quite different order. There may be spindles coming from the back brain and none from the front, or there may be spindles from both but with no correlation in time or wave length, or the patterns from each may be entirely random in an individual way. But if a sudden noise disturbs the sleeper, the sound of a voice or the closing of a door, instantly the pattern from *both* areas changes to trains. Tests show that these noises which initiate trains in a sleeping person have no effect on his wave pattern when he is awake.

Insomnia victims, who find that when they try to make their surroundings very quiet their difficulties increase, may perhaps derive a helpful clue from these experiments. The more quiet a bedroom is the greater is the likelihood for a sleeping person to hear slight noises, footfalls, whispered conversation. But if the bedroom is subject to a constant loud noise of a soothing nature, such as the throb of an ocean liner, the sleeper cannot hear the faint human sounds, and so rests undisturbed. Experiments indicate that the electrical wave patterns are much less disturbed under the latter condition.

Suppose you hypnotize a person. Will his brain waves be those of sleep or of wakefulness? David Slight of McGill University brought a man to the Loomis Laboratory for this test. His electrograms were recorded awake and during normal sleep, and showed characteristic and different patterns for each condition. Then Dr. Slight hypnotized him. A sustained condition of cataleptic rigidity ensued. He appeared to be sleeping. And yet, the trains of alpha waves characteristic of the man awake remained throughout the

hypnosis. At no time did any spindles or random waves appear. It would seem that the hypnotic state is not sleep, if brain waves may be taken as a criterion.

5

But science is just beginning its exploration of this field, and present discussion of brain waves can be little more than an enumeration of interesting phenomena. The results are so many-sided—one might say, so heterogeneous—that as yet the laws of mental activity which these changing electrical potentials obey are unknown. The thing that impresses all investigators is the ceaseless continuity of the activity. This was not expected. "Many of us," as Hallowell Davis recently expressed it, "have thought of the nervous system as a great silent network of neurons activated only in response to sensory stimulation. We must now enlarge our thinking by assuming a constant background of preexisting, and probably spontaneous, activity."

What is this activity? Apparently the effect that is caught by the electrodes and transmitted through the wires is an overflow from a ceaseless interchange of electrical energy generated in the brain cells. The main activity is within. The delicate apparatus picks up only the fragments that spill over from this vast hookup of billions of living chemical batteries. It seems reasonable to assume that coincidences occur in the electrical discharge of these cells. Perhaps thousands or even millions discharge simultaneously many times each second, and their coincidences appear in our detectors and recorders as a pattern of waves. The increase or decrease in the number of cells thus coinciding in their electrical activity may be the factor that determines the changes in frequency and wave length, the disappearance and the recurrence, of the waves.

Whatever their origin, it can hardly be doubted that waves may reveal changes in the mental state of the indi-

vidual. F. A. Gibbs and his associates at the Harvard Medical School have studied many cases of victims of epilepsy, and they find that certain types of brain waves are associated with epileptic seizures, and that in many cases preliminary waves appear to signal the onset of a seizure in advance of any other outward sign. Moreover, somewhat similar changes of wave pattern can be artificially stimulated. Dr. Gibbs had twelve men breathe pure nitrogen to the point of unconsciousness, and the brain waves they gave off during their ordeal were in general of a type similar to those characteristic of certain epileptics. Four other subjects agreed to a treatment which lowers the blood pressure to the extent that blood is unable to reach the brain in normal volume; and again, their changes in wave pattern roughly suggested those of an epileptic. A final test, in which ten subjects overventilated their lungs with air, a procedure which depletes the blood of carbon dioxide, gave similar results. And the interesting sequel is that when ten epileptic patients volunteered for these tests, and were subjected to a nitrogen atmosphere, to a condition of lowered blood pressure, and of overventilation of the lungs, usually the artificially induced condition brought on an eplileptic seizure with its typical waves.

Are brain waves something individual, characteristic of each person like his face or his voice? Hallowell Davis thinks they may be, and is now in the thick of an exciting exploration of this question at the Harvard Medical School. He has found it possible to classify the alpha waves into four general types, and he observes that while the pattern varies from individual to individual, it is fairly constant for each. That is to say, John Brown's rhythm is different from Jack Robinson's, but under the same standard conditions Brown's alpha waves always show the same distinguishing features, and similarly Robinson's are standard for Robinson. Dr. Davis, in collaboration with his wife Pauline Davis, has repeatedly recorded the electrical pat-

terns of thirty-five persons, and thus far they have found no exception to this suspected rule.

Moreover, they have recorded the electrical wave patterns of eight pairs of identical twins, ranging in age from eighteen years to fifty-eight. One pair had a very strongly dominant alpha rhythm, another pair showed no rhythm, and between these extremes the other six pairs showed many variations of wave form which Dr. Davis was able to classify under his four general types. But in every one of these cases both members of the pair showed the same rhythm. The fastest alpha rhythm that these investigators have ever recorded—thirteen vibrations a second—was found in one pair of identical twins, and both twins had it. On the other hand, brothers and sisters who are not identical twins do not always show the same pattern. The evidence suggests that the alpha rhythm reveals inborn characteristics of brain organization—qualities which may be hereditary.

It is all very exciting, very fascinating, and as yet very tantalizing. "Here is a key fashioned by physiology out of radio," said the Davises in a report to the Harvard Tercentenary Conference. "Has neurology a lock which the key can open?"

6

There is another key, an older one, which physiology stumbled upon in chemistry: a marvelously sensitive control centered in the endocrine glands. Not only are the popeyed comedian, the bearded woman, the dwarf, the giant, and the fat lady of the circus victims of defective endocrines; but also many mental cases, the feeble-minded, the idiot, the pervert, and, some may wish to add, the crank and the genius, appear to be among the casualties of abnormal flows of hormones. The human body has seven ductless glands, or seven sets of them: (1) the pineal, hidden in the brain; (2) the two-lobed pituitary, also in the head at the base of the brain; (3) the thyroid, in the throat,

touched on either side by (4) the parathyroids, four in number; (5) the pancreas, adjoining the stomach; (6) the two adrenals, close to the kidneys; and (7) the two gonads. Of these seven, all but the first and the fifth have given evidence of being connected with mental states.

I am using the term mental states to cover a wide range of behavior. It would be simpler if we could restrict discussion to the consciously directed efforts of the brain, and consider only such intellectual operations as were tested by the Benedicts in the metabolism experiments. But the mind not only thinks, it also feels. It is rational, but also emotional. Somehow there are generated or received in the brain the feelings of rage, fear, hate, love, and the rest. Each of these emotions may be curbed by thoughts which also are formed or received in the brain, or, contrarily, each may veto reason and take the helm. It is a matter of common observation that the second alternative is the more frequent occurrence.

Michael I. Pupin once asked Foster Kennedy if the medical men had yet found the part of the brain which governs emotion. Dr. Kennedy, as he told the story[1] in a recent lecture at the New York Academy of Medicine, surprised the physicist by answering, "Yes, in the hypothalamus."

"Ah, but can you pull the switch?" inquired Pupin.

"No," replied the Cornell neurologist, "but another hundred years of peace, and we will be able to! And then the governments of the Earth will establish switching posts throughout all countries, and there will be a great Day, when mankind will come to be switched into happiness. But," continued Dr. Kennedy, "there will be one man in perhaps every two hundred million who will hang back—in uncertainty and discontent. Six months after the switch-

[1] This account is from Dr. Kennedy's lecture "The Organic Background of Mind" which forms a chapter in the book *Medicine and Mankind*, edited by Iago Galdston (1936).

ing, these doubting Thomases will together be lords of the Earth; but six months later still they will have found there is no Earth worth being lords of—for their subjects will not work, they will be only shepherds of sheep. And to make man once more discontented and human, the lords of the Earth will take all the doctors and load them into scows and tow them into the middle of the Atlantic—and sink 'em."

It was Walter B. Cannon and his collaborators who showed the importance of the hypothalamus for emotional reactions. Dr. Cannon further demonstrated that this ancient part of the brain—it can be traced through fossil fish for a thousand million years—operates in close association with the adrenal glands. Suppose an animal sees or hears something which angers him, or frightens him—it makes no difference which, for in either event the thalamus responds the same. It sends a series of impulses through the nervous system. When this excitation reaches the adrenals, the medulla of these glands discharges a hormone into the blood stream, the substance we know as adrenalin. When particles of this adrenalin, carried through arteries and veins, reach the liver they cause it to release into the blood some of its stored-up sugar. Thus the animal, be he man or fish, is swiftly provided with the extra fuel needed for fighting or fleeing. Whether he stays and faces the foe, or runs to fight another day, he will need energy—and by such means the body has keyed its chemical mechanism to supply the fuel at an instant's notice. But the same effect may be attained artificially. The injection of adrenalin into a placid animal or man will induce these same bodily changes, including an ill-defined emotional state. As before the liver will release sugar; the blood through changes of its pressure will be partly withdrawn from the skin and digestive organs and be sent in greater volume to muscles and brain.

A dramatic example of this chemico-mental sequence in action was related by James Bertram Collip, the Canadian biochemist and former coworker with Banting in insulin research. It seems that a diabetic patient took an overdose of insulin, and did not discover his condition until he was walking on the street. Too much insulin depletes the blood of its normal sugar content, and the brain, which must have its fuel, cannot long endure the short rations. The consequences are faintness, incoherence of speech, a convulsive seizure, eventually unconsciousness. Most diabetics carry a bit of sweet in their pockets, and a nibble will soon restore the blood equilibrium. When this person of Dr. Collip's story felt himself getting dizzy he hurried to a near-by drugstore to buy a bar of sweet chocolate, but arrived in such a wobbly state that he was unable to make his wants known. The clerk supposed the fellow was drunk, and threw him out of the store. This act enraged the chocolate seeker. His rage got in its work; his adrenals poured adrenalin into the blood, the adrenalin activated his liver to release sugar, and thus resugared the gentleman regained control sufficiently to proceed to another drugstore and make his purchase.[1]

As the adrenals serve the emotions through their control of sugar, so in their ways the parathyroids seem to serve by their control of the calcium content of the blood. Too much calcium may result in a hyperexcitable state of the nervous system, together with the muscular rigidity associated with tetany; too little has been known on occasions to bring on languor and mental torpidity. Dr. Collip told of a patient in a stupor who could be roused only with difficulty and whose speech was incoherent. Test showed that his blood calcium was only half the normal amount. Appropriate hormonal treatment was given, and "his

[1] Our story would be incomplete if I did not add that the nervous system can bring about equally well all these emergency reactions, releasing blood sugar and changing the blood pressure, *without* calling upon the adrenals. The adrenals provide reserve equipment, to reinforce the nervous system when necessary.

rapid return to normal, both mentally and physically, was truly remarkable."

The gonads, or sex glands, are the manufactories of hormones which exercise profound control over mental states. "The contrast between a *virile* dominating personality and that of a weak whining *emasculate* is all-illuminating," as R. G. Hoskins points out in his book *The Tides of Life.* The late Sir Frederick Mott and others traced an apparent parallelism between dementia praecox and deficiency of this hormone. Indeed there are cases on record in which patients suffering from this mental disease showed marked improvement following medication with the missing hormone—but it is also true that many improved without the treatment. "Altogether," concludes Hoskins, "the relation of the male sex glands to insanity still remains one of the thousands of unsolved problems in endocrinology."

Perhaps the most clearly defined and broadly inclusive control of mental states by endocrine secretion is that identified with the thyroid gland. Children born with defective thyroid equipment show defective intelligence; the extreme consequence is the form of idiocy known as cretinism. When the thyroid output becomes impaired in adult life, the victim's mental activity slows down, initiative wanes, concentration and consecutive thought become impossible. Excessive functioning of the thyroid also is a disease: here the patient is irritable, restless, sometimes obsessed by pathological fears, sometimes swept by hysteria.

One of the triumphs of biochemistry was the attainment of the thyroid hormone in pure state. In a brilliant research at the Mayo Clinic, E. C. Kendall isolated a highly active crystalline derivative. Several years later C. R. Harington, working at Cambridge University, extracted this product more efficiently and in its natural form, identified it accurately, and proved its chemical composition by synthesizing it. Others too had part in this important advance, and today thyroxin is built up in the laboratory like many other

chemical compounds. To thousands of humans this stuff of carbon, hydrogen, oxygen, nitrogen, and iodine has been a true elixir of life, and, what is more important, of sane balanced life. "Not the magic wand of Prospero or the brave kiss of the daughter of Hippocrates ever effected such a change as that which we are now enabled to make in these unfortunate victims," said Sir William Osler, referring to the baby victims of thyroid deficiency, "doomed heretofore to live in hopeless imbecility."

But supreme among the hormone producers is the pituitary gland. Indeed, the pituitary appears to be a master organ which sets the level of life for the other glands. It is known that the front lobe of the pituitary secretes hormones which serve as messengers to the thyroid, the gonads, and the adrenals, and thereby control their growth and direct their functioning. It is difficult to separate the direct physiological consequences of pituitary defects from those resulting from the failure of the other glands which in turn are dependent on pituitary control, but there are diseases which appear to be in the former category. The form of giantism known as agromalgy has been traced to an overactivity of the pituitary. Its victims may show marked mental disturbances and personality changes, ranging from melancholia to manic-depressive insanity and that curious disease of split personality known as schizophrenia. Collip deprived a wolfhound puppy of its pituitary gland. At once it became extremely stupid and timid, and continued so for months. Then he began to treat the animal daily with a pituitary extract, and within a few days it had become bold, aggressive, inquisitive, quite like a normal dog of its breed.

Nor is courage the only moral quality that seems to get its stamp from this distinctive lobe of tissue. Perhaps mother love, the solicitous care of the parent for its child, the home-making and nest-building instinct, also derives from a minute chemical activator which is fashioned here. Oscar

Riddle has discovered that a remarkable influence does issue from the front lobe of the pituitary gland, a hormone which he named prolactin.

Recently, in his laboratory at the Carnegie Institution's Station for Experimental Evolution, I watched Dr. Riddle perform an experiment. He reached into a cage in which a mother rat was nursing her seven youngsters, and took out three of the baby rats. There were rows of many other cages, each containing a rat and labeled with a card which noted essential data of its occupant. Some of the rats were lacking in thyroid glands, some in pituitary, some in other organs; some were males, some females. Dr. Riddle selected three cages at random, and placed one infant in each. Then we stood back in the shadow and watched.

In one cage the rat gave no attention, hardly a glance, to the helpless babe. In another the occupant immediately approached the little fellow, smelled it, and passed on, not interested. In the third the rat showed immediate interest, nosed the baby for several seconds, then picked it up hurriedly, carried it to the nest, and cuddled it solicitously.

Now the extraordinary fact is that this third rat was a male, and the other two were females. Ordinarily males show no solicitude for the young, not even for those of their own household. But this male had been injected with prolactin, and the hormone so dominated him that characteristic maleness was overruled to conform to the maternal behavior decreed by prolactin. Half a dozen other rats were tried in the same way, and the results were similar. The rats being treated with prolactin were interested and solicitous; those in which the hormone had not been injected were indifferent.

Dr. Riddle and Robert W. Bates prepared this hormone from the pituitary glands of cattle, and found that it excites mammary glands to produce milk. Hence the name. Later it was demonstrated that the hormone affects nerve tissue as well, inducing a brooding instinct in fowls and

parental solicitude in rats. After treatment with prolactin, virgin rats build nests over young and care for their adopted little ones. If there are no baby rats available, they will take baby mice as wards, or even newly hatched pigeon squabs. And herein appears a mighty reversal of instinct, since under normal conditions a baby pigeon is the natural prey and food of a healthy rat. No change in human nature could be more radical than this demonstrated change in rat nature.

A curious interrelation which Riddle observed is that full effects of prolactin depend upon a previous action of the two gonadal hormones acting in a fixed sequence. "Thus we here find—I believe for the first time in the psychic sphere—a normal development of response which rests upon a succession or chain of normal actions."

7

Assuredly much more than sugar and oxygen are required to sustain the competent brain. Possibly there are sequences of control yet to be uncovered, versatilities in hormone activation which we do not suspect today. The fact that the injection of minute quantities of thyroxin, a chemical compounded in the laboratory, can transform a child from a gaping idiot into a rational human being, is powerful evidence for the chemical foundation of mind. We may paraphrase and extend: Without that sugar and oxygen—and thyroxin and other essential hormones—there could be no thought, no sweet sonnets of Shakespeare, no joy, and no sorrow.

Very very minute are the quantities of endocrine substances that serve the body; this fact emphasizes the potency of the chemical control. The electrical potentials of the brain, as they are detected by the electroencephalograph, are tiny millionths of a volt. Half a peanut supplies the extra energy for an hour of mental effort—but relatively that is colossal. The hormones that ride the blood stream

on their merciful errands of binding and loosing are vanishingly small portions of matter. One fourth of a grain of thyroxin suffices for the entire human body.

To have detected that dilution, to have isolated its molecule, weighed it, broken it down into its atoms, and then built the thing anew in a test tube, is a demonstration of the adeptness and sureness of our modern techniques. Similar feats are occurring all along the biochemical front today. They strengthen our faith that the chemist of the future will be one of the chief allies of the neurologist, and, perhaps, of the psychiatrist.

Chapter XVI · CAN WE LIVE LONGER?

> Man will never conquer death. For death is an essential characteristic of our self. But he will not tire of seeking youth. Medicine and hygiene have already considerably reduced the number of premature deaths. . . . Some day, almost every individual may reach senescence, and die of old age. Can we progress farther?
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> —ALEXIS CARREL, THE MYSTERY OF DEATH

IN the *Athenian Mercury*, that curious weekly miscellany of questions and answers published in London in the seventeenth century, I came upon this query propounded by a reader 247 years ago: "Whether may a Man preserve his life to extreme old Age, without diminishing of his Senses, or interruption of Health, either by Pains or Sickness?"

"It's reasonable in the Theory," answered the editor, "but difficult in the Practice Part to obtain such an immortalizing Quintessence to preserve or renovate all sorts of Persons." A list of prescriptions follows: the use of diets, consultation of the herbal, the resort to astrology, reading of the stoics, partaking of milk from the rays of the Moon, or a golden elixir from the rays of the Sun, or a broth brewed of the influence of the stars—medicines difficult to procure, the candid editor admits, but "that there are such Medicines is out of Controversy true."

Through the centuries has run a persevering faith in the belief that "there are such Medicines." Perhaps most of it is wishful thinking, aided and abetted by the wiles of quacks, but honest science also has encouraged the idea that the years of a man's life are not necessarily limited to the psalmist's formula of threescore and ten. From early philosophers, down through astrologers and alchemists, the idea has come at last to the test of the research laboratory which calmly experiments. Here chemists, physiologists, endocrinologists, and other biological adventurers are trying various arts and medicinals to see if they can add any days, months, or years of lucid flame to life's brief candle.

Candles and men are subject to accident and may be snuffed out. Both are subject to the laws of thermodynamics and, even if no accidents befall, they burn out. The accidents to which human bodies are liable range all the way from encounters with automobiles to encounters with germs. If an elephant tramples a child we list the cause of death as accidental. If that same child should escape the elephant and encounter a bacterium, and die in a paroxysm of choking, the cause might be recorded as diphtheria—but actually the attack of the invisible microbe is no less accidental than the attack of the massive elephant. Both are external, both are elements of the environment which by chance happen to make contact with the child, and both extinguish a living flame which but for their presence would continue. In this view we may class all contagious diseases, all those biological disturbances which are communicated by a bacillus, a virus, or other agent, as accidents.

Germs and other carriers communicate disease to organs which are open to contact with the external world. At least, these first-to-be-encountered systems would be the ones most liable to attack. I refer to such as the lungs and other organs of respiration (in continuous contact with air from outside), the digestive organs, and others. At Johns Hop-

kins University, where for many years Raymond Pearl and his associates have been making a systematic study of the records of human longevity, Dr. Pearl uses a scheme for classifying the parts of the body into two groups: *first*, those organs which are exposed to external contacts, and *second*, those like the heart, arteries, and veins, which are closed systems and normally have no outside contacts. Recently Dr. Pearl took the records of the 5,985,833 deaths which are registered as occurring in the United States during the five years 1923 to 1927, classified the causes of death in terms of the organs which were diseased, and found this suggestive comparison:

Diseases of organs of the first group were responsible for most of the deaths which occurred between the ages of twenty and twenty-four years, and, to a lesser extent, for most of those occurring up to age forty-five; whereas

Diseases of organs of the second group were responsible for most of the deaths which occurred after age sixty-five, and particularly at age ninety and beyond. (There were 85,039 deaths at ninety and beyond, sufficient to provide a fair statistical sampling of extreme old age.)

In short, it appears from this analysis that most of these young people in their twenties and thirties, and those whose lives were just beginning at forty, died of diseases of organs exposed to contacts with the outer world—presumably a considerable proportion were victims of chance encounters with germs and other accidents; while the ninety-year-olds, with stronger constitutions or greater immunity or better luck, resisted these external foes only to die at last from failure within.

The crucial task in the study of aging is to determine the nature of this failure within.

Do organs irrevocably wear out, overuse their inborn capacity to endure, eventually exhaust their resources in some such inevitable sense as the candle burns up its store of hydrocarbons in the wax?

Or, is organic failure itself an accident, the result of conditions that might be remedied if we knew their causes—or perhaps a consequence of burdensome accumulations in the body mechanism which might be avoided, or of neglect of repairs which might be self-corrected if the body were continuously provided with repair material?

These questions suggest two radically different theories of the aging process. If the second alternative be true, it seems reasonable to expect that a life might be indefinitely prolonged by supplying the body with the necessary wherewithal—assuming, of course, that we can discover what that prime essential is. But even if it should turn out a false clue and we are left with only the first alternative, we still may inquire whether by any means the inborn capacity to endure may not be utilized more effectively, be husbanded, rationed, made to last longer, and so be stretched over a greater span of years.

The experiments with which investigators are pursuing these questions are necessarily limited to the lower organisms. It would be more convincing to have a demonstration made on human subjects, but men and women are not available as laboratory material for tampering with the life span. And so the researchers turn to creatures more amenable to their disciplines. They try out their theories in carefully controlled experiments with rabbits, rats, fish, fruit flies, even the lowly water fleas and the nerveless cantaloupe plants, as samples of the living fire which glows also in the sacred frame of man.

I

That there is an inherent constitutional endowment, an inborn capacity for longevity, has long been accepted on the evidence of human statistics. Family histories show that nonagenerians are usually the descendants of long-lived parents and grandparents. And experiments indicate that the capacity for longevity is handed down from parents to

children with a mathematical precision corresponding to that with which eye color, hair texture, and other physical characteristics are transmitted in the hidden chains of heredity.

Dr. Pearl established this by a series of experiments with the fruit fly. Starting with a single pair of flies as the selected ancestors of his stock, and following their progeny through many generations, he obtained the life histories of thousands of individuals. As each generation emerged from its pupa state (corresponding to birth) he noted the date, transferred all members of the new generation to a new bottle plenteously provisioned with an agreeable banana mash and surrounded by the optimum conditions of air, temperature, and humidity, and awaited their mortality. Some died young, some lived to middle age, a few survived to old age—and it was found that in general a fruit fly lives about as many days as a man lives years. Thus, a forty-day-old fly corresponds in maturity of its life to a forty-year-old man in human life. A ninety-day-old fly is an extremely elderly individual, usually decrepit and feeble.

Among the thousands of individual insects studied in this way there were many of abnormal physiques. They are what the geneticist calls mutants, *i.e.*, changelings or sports. And among the several known types of sports there is one whose distinguishing characteristic is a dwarfing of the wings. The tiny wings look like mere vestiges of the long, broad, overlaid, transparent wings of the normal flies; therefore flies of this mutant type are known as "vestigials." Geneticists had observed previously that they are less robust than flies of the normal type and have a higher death rate, and Pearl's studies now provided an accurate life table. He found that on the average the vestigial flies live less than a third as long as the normal flies.

The next step was to take a female of the normal strain and mate her with a male of the vestigial strain. Some of the

descendants of this crossing were short-lived vestigials and some were long-lived normals, and the distribution of the two types in each generation followed closely the ratios called for by Mendel's laws of inheritance. In repeated trials and variations of this experiment, Pearl showed that the life span is related to constitutional organization—that what is in the egg, the minute arrangement of its genes or protoplasmic units, decrees not only that the fly hatched from that egg shall have dwarfed wings but also that it shall have dwarfed days.

Prior to this work at Johns Hopkins, two biologists of the Rockefeller Institute had observed another line of results from a different series of experiments. Here Jacques Loeb and John H. Northrop were interested in observing the effect of heat on duration of life. They took a number of newly laid eggs of fruit flies, divided them into several groups, and placed each group of eggs in a glass flask plugged with cotton. Every precaution had been taken to guard the experiment against infection. The flies from which the eggs came were aseptic; the flasks and the food within them were sterilized; all conditions except one were kept the same, and that single exception was temperature. Each flask was installed in an incubator held at a different temperature, and the experiment was to see how long the flies would live in each of these climates.

The results disclosed a close correlation. Flies in the clime of 30°C. (86°F.) lived on the average 21 days; those in the more temperate zone of 20°C. (68°F.) averaged 54 days; and those in the chilly world of 10°C. (50°F.) survived for an average of 177 days.

There were, quite likely, various mutants among these flies, possibly short-lived individuals along with those constitutionally predisposed to longevity. The significant disclosure of the experiment is the progressive order of the temperature effect. In each case, the colder the climate the longer was the average duration of life. Heat is used by

the chemist to speed up reactions in the laboratory, and apparently heat has a similar accelerating effect on the chemical reaction which is life.

"If it were possible to reduce the temperature of human beings, and if the influence of temperature on the duration of life were the same as that in the fruit fly," wrote Dr. Loeb, "a reduction of our temperature from (its normal) 37½°C. to about 16°C. would lengthen the duration of our life to that of Methuselah; and if we could keep the temperature of our blood permanently at 7½°C. our average life would (on the same assumption) be lengthened from threescore and ten to about twenty-three times that length, *i.e.*, to about nineteen hundred years."

It is difficult to imagine the human longing for life being satisfied at the cost of the discomfort and inactivity which refrigeration would entail. But assuming that some persons would be willing to put up with a hibernating existence, it is superlatively doubtful, as Dr. Loeb was careful to point out, that this method of life extension can ever be applied to the human species. For, unlike insects, reptiles, and other cold-blooded animals, man does not assume the temperature of his surroundings. Whether he be in an icehouse or a furnace room, a living man's body temperature remains fairly constant around 37°C. Whether some means might be found to induce a state of suspended animation, halt the metabolic processes, and later start them again, is a question that Alexis Carrel discussed in a recent lecture at the New York Academy of Medicine. He suggested the possibility that "Animals could be put into storage for certain periods, brought back to normal existence for other periods, and permitted in this manner to live for a long time." Whether the term animals includes man is not specific in the published form of the lecture.

But temperature is only one of many conditions that change with environment. Suppose the flies were crowded into congested communities, what then? Dr. Pearl arranged

a numerous series of 1-ounce bottles, stocked them with food, and installed various numbers of insects—placing in one group of the bottles 2 flies each, in another 5, in another 10, and so on, increasing the population each time until in the last vials he installed colonies of 500 each. The flies were all the same age, just hatched, and all of the same normal type, but they died at different rates which varied with the degree of crowding. Thus, of 1000 flies which started in bottles with an initial density of 200, half were dead in 7 days, but of 1000 which started with an initial density of 35, 45 days elapsed before half the population had died.

What is this longevity factor which overcrowding may change and temperature may alter? Is it an inherent store of vitality with which each individual is peculiarly endowed at birth? To question that idea, Pearl placed newborn flies in bottles without food. This left them entirely on their own, each individual completely dependent on its inherent vitality—and the flies lived an average of 44 hours. He repeated the starvation test with flies at different densities of population—but crowding made no difference, for death came in about 44 hours for all communities at all densities. He placed flies of the short-lived vestigial strain in one foodless bottle, and flies of the long-lived normal strain in another—but genetic differences gave no advantage now, for in both groups death came in about 44 hours. Apparently the inherent vitality of the individual is not the only fundamental factor which influences longevity, else the two types should show marked differences in survival under the starvation test.

The problem has been further investigated with cantaloupe seedlings. Carefully selected seeds, all taken from the same melon, weighed and graded so as to insure equality of starting conditions, are allowed to absorb all the moisture they can in a three-days' soaking. Then each seed is laid on the surface of a gel of agar in a glass tube, and the tube

is placed in an incubator running 86°F. The incubator is closed and dark within, so no energy of light can reach the seed and aid its growth. The agar is not nutritious and contains no plant food. It merely provides a medium for the roots to grow into, and presently the seed sprouts, sends down a rootlet, pushes up a stem. It grows in a normal way for several days, developing a considerable root system, the stem climbing upward in the darkness and carrying the cotyledons with it, until a maximum growth is attained. Then the seedling remains without visible change for a number of days, not growing but still living, with cells in full turgor, carrying on their normal metabolism: the seedling is in a state of suspended animation.

All this active period of growth and this quiescent period of suspended animation are independent of the environment, speaking nutritionally. Like the fruit flies in the starvation experiments, the seedlings must live on their own resources, on whatever was in the seed at the beginning. Gradually the cotyledons shrivel as their stored-up materials are more and more exhausted, until a time comes when they can no longer support even the restrained chemisms of suspended animation. Then the stem begins to wither with the onset of death.

For some seedlings death comes earlier than for others, but for each of them it was found that the total length of life was directly related to the period of growth. When the period of growth was long, the period of suspended animation also was longer than the average. When the period of growth was short, the period of suspended animation was shorter, and the seedling hastened to early death. A case of wasting its substance in riotous living?

This relation of growth to longevity may be tested also by measuring the amount of carbon dioxide given off by the plant, since this waste is a direct index to the rate of living. There were seedlings that lived 14 days, others 15, still others 16, and it was found practicable to measure the

carbon dioxide produced daily by each of these tiny plants. The daily output for all was averaged, and this was arbitrarily taken as 100 per cent. When the average output for each of the three groups was reckoned in terms of this average for all, the carbon dioxide rate showed as follows:

For plants that lived 14 days, 104 per cent
For plants that lived 15 days, 102 per cent
For plants that lived 16 days, 81 per cent

It is not only a notion we have gained from observation of prodigal sons, but a rather fundamental rule of nature: the faster a body lives, the shorter will be its life.

But the output of carbon dioxide is not the only indicator of rate of metabolism. The consumption of oxygen is another index. The consumption of food is yet another—and here we come to a factor that is of great personal interest and should be directly under man's control.

2

The subject of diets and their probable influence on length of life has been a topic of speculation through the years, both before and since Francis Bacon proclaimed his generalization: "The cure of diseases requires temporary medicines, but longevity is to be procured by diets." This Baconian thesis of more than three centuries ago is engaging the attention of some of the best thought and skill of the biochemical laboratories today. And results are beginning to tell.

At Cornell University, for example, C. M. McCay, W. E. Dilley, and M. F. Crowell came upon a significant outcome while making a study of the nutritional needs of brook trout. It seems that in nature there is a peculiar vitamin essential to trout life—factor "*H*" it is called. The Cornell scientists were interested in seeing just what dietary relationship exists between the level of this *H*, which supplies catalyzing agencies for the fish's living processes, and the

level of protein, which supplies calories for its growth. So they designed a series of diets which were uniformly deficient in the *H* factor but of varying protein content—the diet for one group of trout being 10 per cent protein, that for another group 25 per cent protein, another 50, and a fourth 75 per cent. The uniform deficiency of *H* doomed all the fish to premature death, but the experimenters wondered if the different amounts of protein would have any effect.

It was known that food containing less than 14 per cent protein is insufficient to provide the fuel necessary for growth, though it will sustain life if all other essentials are present. The experiment confirmed this. For the group whose diet contained only 10 per cent protein did not grow another perceptible gram, whereas the fish in the other three groups all grew, and, despite their varying rations of protein, all grew at the same rate. Also they all died at about the same rate, in 12 weeks. But the trout in the first group, those that had failed to grow, lived on the average twice as long. These results suggest that there is, to quote Dr. McCay, "something consumed in growth that is essential for the maintenance of life." He and his associates resolved to investigate that "something" and uncover its effects in a higher order of animals.

They chose as the subject for their new inquiry the white rat. Perhaps no other animal has been so variously experimented upon, and of hardly any creature below man is there so much factual knowledge of its biological nature. The nutritional requirements of the rat are similar to those of man; therefore for food experiments a colony of rats substitute very well for a colony of human beings, and with advantageous economy both of provisions and of time.

The rat experiments at Cornell were conducted jointly by McCay, L. A. Maynard, and Crowell. They took 106 baby rats, born of parents closely akin genetically and, therefore, presumably of the same general heredity, and as soon as the animals were weaned divided them into three groups.

Group I, consisting of 14 males and 22 females, were provided with a completely balanced diet containing also extra calories to sustain rapid growth, and were fed this rich food throughout their lives. Before 1200 days had passed all were dead.

Group II, 13 males and 23 females, were provided with meager portions of the same diet. On these spare rations they grew very slowly but showed a capacity for growth at practically all ages. After 28 months of this parsimonious feeding they were placed on the abundant fare of Group I and throughout the rest of their lives were free to eat all they desired. After 1200 days of the experiment, 8 of this group were still alive.

Group III, 15 males and 19 females, were fed abundantly for the first 2 weeks, the same as Group I. Thereafter they were restricted to the short allowance of Group II until 28 months had passed, when all were put back on full helpings and permitted to feast at will. After 1200 days 5 were still alive.

In all three groups some individuals died early, some in middle life, and, as is true of human society, more females than males survived to old age. The oldest male lived 1321 days, the oldest female 1421 days, and both were of Group II. When all results were averaged for each group, they gave these values:

	Average span of life	
	Males	Females
Group I	483 days	801 days
Group II	820 days	775 days
Group III	894 days	826 days

The tabulation shows that the male rats whose early growth had been retarded lived nearly twice as long as those that had known no restraint. For the females the averages are not conclusive. Ordinarily they have a life

expectancy about 10 per cent greater than that of males: but why the females of Group I should outlast the males of the same group by almost another lifetime seems inexplicable. The low average for the females of Group II may possibly be accounted for by the death of two young lady rodents during a spell of hot weather early in the experiment, and these premature losses distort the data. But despite the relatively low average of the females of Group II, 5 of them were alive after all of Group I had died.

In general the full data strongly suggest the presence in Groups II and III of some factor which tended to promote longevity and whose effect was more marked with males than with females. Nor is the number of days the only index to the operation of this unknown factor. Age for age, the rats of the retarded groups looked younger than those of the group that had matured rapidly. Their fur remained soft, silky, and thick well into the third year, in striking contrast with the coarse, unkempt, scraggy hair of the equally aged animals of Group I.

These results seem in accord with Pearl's findings from the cantaloupe seedlings. Further confirmation is lent by a series of investigations lately reported from Brown University. Here Lester Ingle and Arthur M. Banta have been experimenting with the large water fleas known as daphnia—really not fleas, but a species of small crustacean. They find that when these creatures are fed full rations of food throughout their lives from birth to death their average life span is about 29 days; whereas those fed half rations for the first 14 days, and thereafter given full fare, live about 50 per cent longer to an average span of 42 days. A regimen of frugal eating would appear to be a fundamental requisite for long life if we are to take at their face value the results of these ingenious trials of cantaloupe plants, water fleas, and white rats.

The Cornell experimenters do not regard their search as concluded. They are pushing forward with a new program

in which they plan to repeat the experiments, using larger colonies of rats, and also at the same time to pursue some promising bypaths which their earlier studies opened. For example: post-mortem examination of the hearts, livers, bones, and other internal organs of the subjects of their former experiments showed certain changes following the limited diets. The new study will seek the meaning of these changes—whether any of them have to do with the retention of physical and mental vigor into old age. Another bypath to be explored is an inquiry into the value of physical exercise—whether exercise after middle life hastens or delays senile changes. For the complete program of old-age research a 6-year schedule, already begun in 1936, has been laid out.

3

Meanwhile, at Columbia University, Henry C. Sherman and his associate Harriet L. Campbell have been investigating dietary effects to determine the ingredients of food that contribute to length of life. They have found unmistakable evidence that calcium is a factor, and Vitamins A and G are also indicated as probable factors. The experiments are still under way, but the results already attained are so convincing to Dr. Sherman that he is applying them in his own eating. He believes that by including in the daily diet of a lifetime a liberal allowance of food rich in calcium and in the two vitamins, 6 or 7 years may be added to "the period of the prime."

This Columbia work grew out of an investigation begun in 1918, when the shortage caused by the World War made it important to know what food combinations would stretch farthest without risk of undernourishment. Specifically, Sherman took the two most common foodstuffs, wheat and milk, and undertook to find what is the smallest proportion of milk that will supplement wheat to form a nutritionally adequate diet. He used hundreds of white rats for the test,

feeding each group a different combination of milk and wheat, allowing all to eat at will and as much as they pleased, and then watched the course of their health and general vitality under these different feeds.

Diet *A* consisted of five-sixths ground whole wheat mixed with one-sixth dried whole milk. Diet *B* contained twice as much milk, the proportions here being four-sixths and two-sixths. It was found that diet *A* supported normal growth and health, that it was adequate, therefore a permissible diet; *but* that diet *B* gave an even higher average result. When he tested this higher average further in terms of length of life, Sherman found that the animals on diet *B* lived about 10 per cent longer than those on diet *A*.

Why?

The explanation must lie in the milk, since the only difference between the two diets was in the proportions. The problem became one of identifying the component of milk that carries the longevity promoter.

Milk is a fluid of exceeding complexity. It embodies proteins, carbohydrates, fats, all the known vitamins, and several mineral elements. Any complete analysis of this complicated mixture, and trial of its substances one by one, would be an almost interminable task. But there are certain ingredients that are prominent or that for various biochemical reasons may be considered suspect, and the Columbia chemist went after them first. Calcium, for example, the well-known metallic constituent of lime which is necessary to bone building, is a prominent constituent of milk. Dr. Sherman took diet *A*, with its five-sixth wheat and one-sixth milk, and added to it a carefully measured quantity of lime—a quantity just sufficient to provide the calcium that would be carried by an additional one-sixth of milk. Thus he attained a combination that was diet *A* in all ingredients but one: in calcium content it was the same as diet *B*. When he tried this calcium-enriched food

on a large group of rats, feeding a control group on unenriched diet *A* at the same time, he found that the calcium eaters lived on the average longer than the diet-*A* eaters.

Milk is rich also in vitamin A, while wheat contains very little. Butterfat too is rich in vitamin A; and by adding to it a measured portion of butterfat, diet *A* was made as rich as diet *B* in vitamin A without introducing the other significant components of milk. Thus it became practicable to test the influence of a double portion of vitamin A in food, and the results gave strong presumptive evidence that this vitamin is a longevity promoter. By similar methods, circumstantial evidence was found pointing to vitamin G as a third agency that contributes to length of days.

The three longevity factors—calcium, vitamin A, and vitamin G—are absent from, or very meagerly present in, cereals and many other foods. But they are all present in milk. The two vitamins, and to a lesser extent the calcium, are present in fresh fruits and vegetables. Dr. Sherman therefore advises those who aspire to long life to make milk, fresh fruits, and vegetables important members of their daily diet. As a practical formula for insuring ample portions of the longevity factors, he suggests that at least one-fifth of the family food budget be spent on milk and cream, and not less than one-fifth on fresh fruits and green vegetables. This leaves three-fifths for meat, bread, butter, eggs, tea, coffee, and condiments, including all sweets.

Animals on the diet enriched by calcium not only lived longer, but their rate of growth was more rapid than that of those on diet *A*; while those on the low-calcium diet grew to maturity more slowly and died earlier—a result which seems quite the opposite of the Cornell result. But Dr. Sherman doubts if the two sets of experiments are necessarily in conflict. The starting point of the Cornell studies was a diet rich in practically all food components, and especially so in proteins; and the results show that re-

straint is desirable. The starting point of the Columbia experiments was an abstemious diet, a "poor man's fare" such as most people must live on; and the results show that certain small improvements in this relatively inexpensive diet have a beneficial effect both on growth and on longevity.

As a crude analogy we may liken the life cycle to the path of a projectile launched into space with an initial propulsion that may send it a certain maximum distance. But the distance may be shortened by wind resistance. The initial force is analogous to the genetic constitution or heredity which imparts momentum to the life and determines how far it may reach. The loss of momentum through wind resistance is analogous to the shortening of a life span by an overrapid rate of living. But, Dr. Sherman points out, there is another possible element in the picture. There are some projectiles, torpedoes, and rockets which are not wholly dependent on the impetus of the initial force. They generate additional propulsive power during flight, and so are able to go farther. We are to think of the protective foods as supplying additional propulsion, as neutralizing to some extent the forces of degeneration and death, and so as prolonging the life cycle.

4

There is another approach to this problem. We observe that certain forms of life never grow senile. Leo Loeb has pointed out that cancer cells may be called immortal, since they outlive many times the natural life of the mouse in which they originated and have continued to live through successive transplantings with every reason to believe that the sequence may be prolonged indefinitely. The "deathless" chicken cells at the Rockefeller Institute were twenty-five years old on January 17, 1937, and I have no doubt that long after our generation has passed some historian

will be recording their hundredth anniversary. It is our complexity that dooms us: the multiplicity of specialized mechanisms that must be in step, in synchronization, continually interacting in the complicated teamwork of interdependent organs. Perhaps no one dies of old age; it is the failure of a gland to secrete an indispensable hormone at a critical moment, the drying of the tissues, the heightening of blood pressure, the thickening and hardening of the arteries. Nor is it only the veterans of eighty and beyond that are victims of these diseases.

"If we take as our criteria the usual specifications for old age used by the medical profession—arteriosclerosis, hypertension, tissue dehydration, and the rest—we find that numerous people die of 'old age' anywhere between forty and one hundred and forty years," said William Marias Malisoff. "This indicates either a very unstable state of affairs, or the wrong definition of old age. On the first alternative the span of life cannot be said to be 'fixed.' On the second, no one can be said to have lived out his span. There are at least 5000 people in the centenarian range in the United States. They are evidence that 'centenariness' is a persistent thing, else it would have bred out quite thoroughly long ago through intermarriage.

"We look for clues. The outstanding correlation between a physical characteristic of the body and the age of the body is a deposition of lipoids in the arteries, notably in the large aorta. If that is primary, surely we can interfere with old age. If it is secondary, we have many clues from diseases, such as diabetes, which may put us on the trail of the primary process, which process in turn probably depends on a hormonal disturbance or is a hormonal disturbance. Our problem may reduce to one of supplying hormones or their equivalent. There is increasing evidence that all hormonal substances eventually will yield to synthesis, either to chemical synthesis in a test tube or to biological synthesis outside the human body—as, for ex-

ample, adrenalin, insulin, and thyroxin are now being synthesized. Thus it becomes possible that old age may be alleviated by supplying the missing factors."

Can that possibility be tested and its probability be determined? Dr. Malisoff, a physical biochemist working first at the University of Pennsylvania and now at the Montefiore Hospital in New York, has been studying the problem of aging from the point of view just outlined. Lipoids are insoluble substances such as fats and the solid alcohols known as sterols, and among these sterols is a white material which the early chemists found in bile. They named it "cholesterol," meaning bile solid. Afterward the analysts identified cholesterol in a variety of animal material. It is an ingredient of egg yolk, of nerve tissue, and of brain cells, it clots in certain organs to form gallstones, it deposits on the eye to form a cataract, and its gradual accumulation in the walls of the blood vessels is a mark of arteriosclerosis.

Accepting this effect of cholesterol accumulation as one of the most important indices of what occurs in aging, Malisoff interprets it as related to a general diminishing of the oxidation processes of the body. The dumping occurs, apparently, at points of least resistance. But why does it occur? Probably because of the absence of something which can oxidize cholesterol—something which is abundant in youth but scarce in old age.

Cholesterol is insoluble in water. But Malisoff demonstrated that by a vibration of sound waves he could cause a solid mass of cholesterol to break up and become finely dispersed through the liquid. Later, working with F. A. Stenbuck, he made a finely dispersed solution of cholesterol and subjected the mixture to short electric waves, of 5 meters wave length. The effect of these electrical vibrations pulsing through the solution was to cause a dilution of the material by about 25 per cent. Apparently the electric waves caused the particles of cholesterol to cluster, to coarsen, and thereby to reduce the total surface of material

in solution, giving an effect of dilution. Chemists call this process "aging." It seems to be well named.

The foregoing studies were made in glass beakers, not in living material; but in 1936 Malisoff began a series of experiments with rabbits, following a trail that was blazed in Russia many years ago. There, in the old St. Petersburg, a physiologist Ignatowski found that when rabbits were denied their customary vegetable food and made to live on a diet of eggs, beef, and milk, they developed hardening of the arteries. Later investigators showed that the meat and the milk had hardly any effect in this direction, but that a diet of egg yolks alone would induce the disease—also a diet of brains. Both egg yolk and brains are rich in cholesterol. Later two other Russian experimenters, Anitschkow and Chalatow, fed straight cholesterol to their rabbits and found it even more effective in bringing on the arterial hardening.

An animal accustomed to an herbiverous diet may be expected to have less adequate means for coping with unaccustomed ingredients of a carniverous diet, so we are not to conclude that because yolk-eating rabbits develop hardening of the arteries yolk-eating men and women are courting the disease. Not necessarily. The point is that this experiment provides the research scientist with a means of inducing the condition of arterial hardening at will, and thus facilitates inquiries into the nature and cure of the disease.

It is believed that the thyroid gland is one of the body's defenses against arteriosclerosis. Two Japanese investigators, Marata and Kataoka, found that thyroid extracts administered to rabbits were moderately successful in combating the disease. H. Unger, at the University of Jerusalem, tried iodine and found that it had a neutralizing effect on cholesterol accumulation. Malisoff's experiments at the Montefiore laboratory are an attempt to test and extend these ideas. He picked at random twelve young

adult rabbits from a thoroughbred group, and by surgery deprived each rabbit of its thyroid gland. The rabbits were allowed to eat their green vegetables and other customary food at will, but in addition each rabbit was fed daily a pellet of pure cholesterol, the pellet being wrapped in a cigarette paper and soaked in sugar to make it palatable. Thus deprived of their thyroids and dosed with cholesterol, the rabbits might be expected to develop hardening of the arteries, unless some defense against the disease were provided artificially.

The defense which Malisoff had selected to try was the powerful KCNS, potassium thiocyanate. This compound is a very effective dispersing agent, is found in body fluids, and is not poisonous. It operates by furnishing thiocyanate ions, whose negative charge is important in dispersing cholesterol. To four of his rabbits Malisoff gave each day 60 milligrams of the thiocyanate; to another four he administered the lesser dose of 20 milligrams daily; and the remaining four were fed no thiocyanate, but left on their own resources entirely, as a control group.

At the end of about 60 days the twelve rabbits were killed. The four that had received no thiocyanate all showed very pronounced conditions of arteriosclerosis, with deposits of cholesterol both in the aorta and in the kidneys. The four that had received 20 milligrams of the thiocyanate showed the disease in a milder form. The four that had received 60 milligrams of the drug showed no hardening. Apparently the effective dose for the rabbit lies somewhere between 20 and 60 milligrams. And the experiments seem to indicate that potassium thiocyanate exercises a protective action against the deposition of cholesterol in rabbits. But rabbits are not men, and their diet is normally quite different from human diet. So Malisoff is now planning to push his research into higher levels of life, to try the effect of the drug on animals nearer to man. Also he is trying other substances to test his other theory that the cholesterol

deposition is a consequence of the failure of the body's oxidation processes.

"A theory is only a guide to the searcher," explained Dr. Malisoff. "This one says to me, 'Look for oxidation promoters, especially of cholesterol.' These promoters, if found, may help the body to regain its youthful potential, rate, and quality of oxidation. At any rate, like insulin in a diabetic, they may help to postpone a showdown for a long time. The argument will be materially strengthened if the oxidation products of cholesterol should turn out to be substances which normally decrease in old age—such substances, for example, as the sex hormones."

5

The approaches to our problem are many, the methods are diverse, the results are yet to be correlated. To all our hopes and encouragements we have to add the qualification, *not proved;* perhaps, with faith, we may say, not *yet* proved. Many realists question whether effects which are demonstrated in lower forms of animals are necessarily true of man. It may be, though, as Max Rubner suggested years ago, that length of life is a function of evolution. Dr. Rubner made a study of the metabolism of a wide range of organisms, and found a certain ratio existing between the size and metabolic rate of animals and their characteristic life span. Thus, for a large group of warm-blooded animals, including the horse, cow, dog, cat, and guinea pig, he observed that after reaching maturity the animal expended about 200,000 calories of heat energy for each kilogram of body substance, and then died. But when he came to man the ratio was quite different. During an adult human life, extending from age twenty to age eighty, Rubner reckoned that 775,000 calories per kilogram of body weight are expended before the machine gives way. If these calculations are correct it would seem that man has attained a superior position in the race with time. If haphazard evolution has

done that much for us, what might be accomplished if man took the all-important business of evolution into his own hands?

A biologist has already considered that question in public. I quote from J. B. S. Haldane's *Possible Worlds:* "In the rather improbable event of man taking his own evolution in hand—in other words, of improving human nature as opposed to environment—I can see no bounds at all to his progress. Less than a million years hence the average man or woman will realize all the possibilities that human life so far has shown. He or she will never know a minute's illness. He will be able to think like Newton, to write like Racine, to paint like Fra Angelico, to compose like Bach. He will be as incapable of hatred as Saint Francis. And when death comes, at the end of a life probably measured in thousands of years, he will meet it with as little fear as Captain Oates or Arnold von Winkelried. And every minute of his life will be lived with all the passion of a lover or a discoverer. We can form no idea whatever of the exceptional men of such a future."

"Less than a million years" is indefinite and sounds remote, but science has a way of accelerating its fulfillments, and possibly in our groping experiments today we are laying the foundations of such a future. In the search for a Methuselah formula many clues must be sifted. The aging process needs to be studied with something of the comprehensiveness of the research that has focused on the processes of growth. Significant are the studies of the physiology of old age recently carried on at the Nutrition Laboratory in Boston by Francis G. Benedict and his associates. We may expect other specialists to explore further the biochemistry and the biophysics of the human body in its transformations with time, in its sequences from heredity, in its reactions to vitamins, hormones, and other elixirs. For "that there are such Medicines is out of Controversy true."

Epilogue · THE PROMISE OF SCIENCE

Oh science, lift aloud thy voice that stills
The pulse of fear, and through the conscience thrills—
  Thrills through the conscience with the news of peace—
How beautiful thy feet are on the hills!

—W. H. MALLOCK, LUCRETIUS ON LIFE AND DEATH

THERE is another sense in which the frontiers of science and of the sciences are borderlands—the sense in which Petrarch, from the vantage point of the Renaissance, surveyed the human scene. Turning his gaze to the past, wrapped in its graveclothes of history, he saw the dark ages of drift and blind struggle, centuries of eclipse and blunderous groping when but for the dim torch of learning kept alive here and there, in monastery, in university, and in alchemist's cell, it would seem that the human spirit must have lost its way. And then, looking to the future, veiled in its mists of destiny, Petrarch glimpsed the aura of the coming civilization. "Here stand I as though on a frontier that divides two peoples, looking both to the past and to the future." And so it may be with us. These borderlands of research divide more than knowledge from ignorance. They can, if man's will and effort are alive to their opportunity, divide hope from despair, achievement from frustration, a new humane civilization from the old jungle of laissez faire.

As an indicator, compare the treatment of disease today with the medical practices of our forefathers. In 1732, when George Washington was born in Virginia, the average life expectancy of a baby was about thirty eight years. Today an infant can look forward to about sixty years. Washington was luckier than average, for he lived to be nearly sixty-eight, but even then he seems to have died unnecessarily soon. Recently Creighton Barker of the Yale Medical School examined the records of Washington's last illness at Mount Vernon, and from all the evidence Dr. Barker diagnoses the disease as septic sore throat. The former President had the best medical skill of his day. During the 24 hours of his illness the physicians bled him four times, thus needlessly weakening him, and Washington died (says Dr. Barker) of a virulent streptococcus infection. In the corresponding month of 1936, just 137 years later, a son of the President of the United States was stricken by the same disease. The medical men who attended him drained away none of his blood, but instead fortified it by the injection of a newly discovered chemical compound, and the young man rallied to a rapid recovery. The directness and precision of the 1936 treatment compared with the fumbling empiricism of the 1799 treatment emphasize the change which has come in our therapy. They suggest that the revolution which is reshaping medical science is not merely a fight against death, but also a fight for life, with all the implications both economic and social which emerge from science's successful lengthening of the life span. The society which fosters research to save human life cannot evade responsibility for the lives thus extended. Its science must go farther: not merely conserve life, but conserve living.

Indeed, our techniques are yet in their infancy. What we know may be as only a few shells picked from the shore when compared with the vast sea of our ignorance, but what we know is colossal compared with the knowledge we have put to use. "The great scientific revolution is still to

come," says John Dewey, and "it will ensue when men collectively and cooperatively organize their knowledge to achieve and make secure human values."

Such values as international peace, industrial plenty, economic security, physical health and long life for an overwhelming majority of the population, are among the practical possibilities of the revolution which Dr. Dewey foresees. But the kingdom cometh not with indifference. It has to be planned for, organized, programmed, integrated. It has to take into account all resources, all needs, all risks, all limitations. The supreme economic lesson of the 1930's is not a demonstration of the inevitability of the business cycle—possibly there is no such inevitability. Nor is it a proof of the folly of trusting paper values, market booms, and other incitements to the gamble. No, *the* lesson is the exposure of the disparity that exists between (1) the richness of knowledge and of skills which we possess, and (2) the paucity of the use which we make of this knowledge and these skills.

"The depression is a small price to pay," continues Dr. Dewey, "if it induces us to think about the cause of the disorder, confusion, and insecurity which are the outstanding traits of our social life. If we do not go back to their cause, namely, our *halfway and accidental use of science*, mankind will still pass through depressions which are the graphic records of our unplanned social life. But it is incredible that the men who have brought the technique of physical discovery, invention, and use to such a pitch of perfection, will abdicate in the face of the infinitely more important human problem."

Discoverers, inventors, and engineers will not willingly abdicate in the face of any problem. But the human society which is to benefit from their services must understand their standards, collaborate in their plans, and sustain their efforts wholeheartedly, if it is to reap the full returns of the collaboration. Society, not science, is the greater loser from

the lack of cooperation. Indeed, the scientist will keep at his work regardless of outside cooperation or encouragement, and characteristically is little concerned with popular opinion of what he is doing, "quite indifferent," H. G. Wells has said, "whether people like or dislike the knowledge he produces." Not so is the characteristic attitude of the artist, who must have an audience. "Aesthetic life is conditioned by the times; science conditions the times."

Inevitably it conditions the times, and when the times are out of joint we may look to our science not only as a cause but as the remedy. "Do men gather grapes of thorns, or figs of thistles?" It is not enough to learn that grapevines produce their characteristic fruit, and fig trees theirs. Wisdom bids us use this knowledge to its utmost: to plant, husband, and cultivate the vines and trees, to select and improve the stock, to fertilize and encourage the yield, to work systematically for the fullest possible fruitage. A halfhearted acceptance of science, an approval of the laboratory with reservations, an agreement to use its method provided certain sacred cows are not molested in their immemorial fevers and itches—such tactics mean scarcely more than a grudged sampling. There must be no favoritism of the searchlight. A truly scientific and humane civilization can allow no exemption from the challenge of truth, will set up no taboos on the search for truth, and will shackle no truth when found. "Nothing in life is to be feared," said Marie Curie, "it is only to be understood."

I

If science were widely understood, undoubtedly it would be more widely used. If its method were clearly grasped by the lay mind, not only here and there by a few alert individuals but by the great generality of the people, if its present accomplishments were perceived as the predictable effects of certain natural causes, and not as an incomprehensible magic invoked by experts—in short, if science

were popularly accepted as the human adventure and the humane discipline it is, the demand for its extension would be universal. We should hear no more proposals that scientific research take a ten-year holiday to give the world time to catch up. Seeing what research has done in those fields where it has been used, we should urge—nay, we should demand—that its technique be applied to the other fields where it has been only toyed with or ignored. If our social inventions have not kept pace with our mechanical inventions, if our morals are not abreast of our technologies, if our snarled interhuman relations are so lacking in the discipline and the

> keen
> Unpassioned beauty of a great machine,

can we expect to improve the one by anesthetizing the other? The scientific method of thinking is not restricted to one kind of phenomenon, nor is its use confined to persons who have been technically trained in science. Perhaps the world of interhuman relations will never catch up with our technological world of electronic relations (as embodied in telegraph, telephone, electric power, and radio mechanisms) until governments and societies adopt and put to work in that realm the same principles of inductive reasoning, the same methods of experiment, and the same attitude of open-minded seeking which produced the age of electricity.

In considering the departments of organized knowledge, there is a tendency to overrate the so-called exact sciences, and consider that a study is important in proportion as it lends itself to stratagems of measurements. "Only geometers may enter" was Plato's sign over the entrance to his *Academe*, and there are those who would picket the temple of science with the same restriction. It is true that measurement is the indispensable tool of scientific inquiry, and that in some realms of nature our feints at measure-

ment are less clumsy and fumbling than in others. The psychologist finds it more difficult to mathematize in his field than the geneticist does in his, but the geneticist would never be admitted to Plato's grove in advance of the more mathematical radiologist. Surely, though, the whole Universe is open to science, and each field must be explored with whatever tools we can use today or extemporize for tomorrow, never forgetting that the flint axes of the Old Stone Age had to precede the sharp cutting edges of the Bronze Age. Mathematics, which seemed so alien to biology in the nineteenth century, is making sturdy advances in that field today, and with its use is coming a nearer approximation to precision and a surer understanding and control of the life processes.

Years ago Charles W. Eliot said, "The human race has more and greater benefits to expect from the successful cultivation of the science which deals with living things, than from all the other sciences put together." Today we see that the science which deals with living things is not something apart in an airtight compartment, but must deal also at every turn with inanimate things—such things as x-rays provided by a physicist, hormones provided by a chemist, even helium which was first sighted by an astronomer. All our ultimate lands are borderlands, extraterritorial, common country.

The gains that have recently come to biology through the application of physical principles and instrumentalities to protoplasmic problems, are many and obvious. It seems possible, as A. V. Hill has mentioned, that biology may contribute reciprocally to our understanding of physics. Certain strange aspects of matter and energy presented by modern quantum theory may be consequences of limitations within the nerve mechanisms by which we perceive and know. It is possible that the apparent discreteness or lumpishness of the physical world is the pattern in which the brain receives, records, and recalls its impressions of external nature, just as the colors of the rainbow are the pattern

in which our brain responds to the impact of radiation on the optic nerve, though it is insensitive to other "colors" beyond the visible. Nor is it only physics that may be illuminated by biology: each science may contribute some glimmer of understanding to the others, and only by considering all may we come to a workable understanding of any phase of nature (including human nature). Science needs not only the specialization which has uncovered its minutiae of innumerable threads of knowledge, but also the synthesis which will take this vast scattering and weave a fabric for enduring service to mankind.

"Science today, it should be remembered," said Isaiah Bowman, geographer and President of Johns Hopkins University, "means not merely the physical and biological (including medical) sciences, but also the social sciences—modern economics, sociology, statistics, and related subjects—that we now seek to develop in a way as nearly objective as the nature of the human materials and the available techniques of investigation permit. In our time the highest hope of social advancement is based on a reasoned relationship of man to man, not a haphazard relationship. We have come to believe that the affairs of man are not subject to a malign fatalism as he goes forward in his 'dark striving toward the good.' Science is in relentless pursuit of power to diminish the darkness of that striving and to 'shape reality from hope's vast dream.' "

Hope's vast dream is built of innumerable individual yearnings of human minds, and it may be audacious to assert that by applications of the data and methods of science all these personal aspirations will be realized. But so much can be done, so much is plainly waiting to be done, and for so many problems the basic data and methods are already at hand awaiting trial, that we need not worry about the scope of possible futures.

"Under a just and humane government," says Edward M. East, geneticist, of Harvard University, "the machine can abolish poverty. Indeed, it can furnish creature com-

forts amounting to luxury, although, with the inculcation of healthy ideals, inordinate demands for luxury may be expected to diminish. Birth control can lay the Malthusian specter of overpopulation and keep the census figures at somewhere near the optimum for effective effort. Genetic information, sanely directed, can lessen the proportion of the mentally and physically deficient, and can raise the average intelligence materially."

"If the devices of social invention are able to keep pace with the scientific organization of nature, our new road may lead to a fairyland of achievement," says Charles E. Merriam, political scientist, of the University of Chicago. "The burdens of hunger, disease, toil, and fear may be lifted. The book of leisure may be opened, and the treasures of human appreciation and enjoyment made available to the mass of mankind."

And from Russia echoes the confidence of Pavlov, the physiologist: "Let the mind rise from victory to victory over surrounding nature, let it but conquer for human life and activity not only the surface of the Earth, but all that lies between the depth of the sea and the outer limits of the atmosphere, let it command for its service prodigious energy to flow from one part of the Universe to the other, let it annihilate space for the transference of its thoughts. Yet the same creature, led by dark powers to wars and revolutions and their horrors, produces for itself incalculable material losses and inexpressible pain, and reverts to bestial conditions. Only science, exact science about human nature itself, and the most sincere approach to it by the aid of the omnipotent scientific method, will deliver man from his present gloom, and will purge him from his contemporary shame in the sphere of interhuman relations."

2

Our contemporary shame in the sphere of interhuman relations is not a product of science, though science has been

mightily prostituted to the dark purposes. War is an activity willed by maladjusted man—or resorted to by terrorized man—and then waged with whatever instruments lie at hand or can be fashioned to use. Defensive war had its place in the long climb from savagery. By means of organized defense the earliest civilization fought off the earliest barbarians, and culture won peace and leisure for its first tentative footholds. The tragedy of our contemporary shame, as Stanley Casson has pointed out in his *Catastrophe and Progress*, is this: that man should have come so far in mastery of nature and in cultivation of human nature and its relations, and still have to resort to so primitive a system for preservation. War like the bronze artifact belongs in the history of civilization, but its place is far back in the Bronze Age.

War would be unthinkable in a truly modern, that is to say scientific, civilization. The fact that war is so frequent and so overshadowing a concern of the nations is an index to the degree by which they lack civilization. Despite the tremendous demands that are made upon the laboratories by the military and naval ambitions of the nations, and the vast subsidies that are provided for research in matters of defense and offense, science flourishes best in times of tranquility and good will. "Give me a hundred years of peace," says the scientist, again and again, as a condition to the promised conclusion of some important investigation or application. An invariable toll of war is to deflect into narrowed channels the programs of search and research.

Whether war arises out of economic determinism, or out of the perverseness of human nature, or out of some other deep-rooted motivation, no authority has been able to give a satisfactory analysis. I think the advancement of science, its extension into all realms that offer possible fields of application, and, along with this, the spread of the scientific method of thinking, holds out the greatest single promise of amelioration.

Take, as an extreme case, the hypothesis that war is the consequence of an instinct of the human mind, an idea that has vogue among a large element of the population. From this it is argued that war is inevitable, it possesses an inescapable aspect. But when we find biologists treating mental diseases with chemical compounds and getting favorable results, it may be argued that the disease of belligerency, of intolerance, of the lust to kill, is no more inexorable than any of the other mental diseases. If it should be found that a hormone or other compound will mitigate the traits which moral suasion has failed to move, I suppose no orthodox scruples would be entertained in opposition—just as none of the watch and ward societies has objected to the use of thyroxin in treating cretinism and thereby relieving the victim's mental infirmity. The fact that prolactin seems to induce a brooding instinct in fowls and parental solicitude in rats, suggests that mother love may bear some relation to a hormone; and if so sacred and instinctive a quality is thus influenced, then perhaps we may with reasonableness look for biochemical activators of the humane traits of tolerance, pity, neighborliness, and cooperativeness.

But these disciplines, as applied to the renovation or adjustment of twisted mentalities, are still in their very young infancy. For the present, and indeed as preparatory to everything that the future may promise, the most immediate tool is education. It is a tool both for the shaping of minds and characters and for the paving of the roadway toward that future society which Josiah Royce called the Great Community.

H. G. Wells's statement, made shortly after the World War, in which he said that the future of our torn civilization depended on the race between catastrophe and education, has become almost a quip. To some it has seemed another race between the hare and the tortoise, with the hare awake and running every minute of the time. There are

those today who say that catastrophe has well-nigh overtaken us, that not much time is left for education. But there are others who are hopeful, and among them are many scientists and other objective watchers of the terrestrial scene.

3

Oscar Riddle, whose important work in endocrinology has been touched on earlier in these pages, is one of the hopeful scientists. Dr. Riddle observes that most of the advances which man has made in the last 300 centuries are attributable to environment, *i.e.*, to education or changes imposed from without, rather than to heredity, or changes imposed from within. I am privileged to quote from Dr. Riddle's unpublished lecture:

"Scattered, hunted, roving mankind of 30,000 years ago exhibited something more of the appearance, and many more of the traits, of his apelike ancestry than does civilized man of today. The two kinds of men—they would be astonishingly strange and foreign to each other—probably differ very little in the genes or hereditary factors carried by them; and their very marked physical and mental differences rest largely, or almost wholly, on what a gradually accumulated 'social environment' has contributed to modern, educated man. Quite in accord with this is the fact that most criminologists nowadays find it advantageous or necessary to consider all human infants as essentially young savages in which criminal or asocial tendencies are eradicated only by the socializing influences of parents, associates, and the many aspects of community life. In other words, educated men and women of today probably owe their advance over a rather ugly primitive man of 30,000 years ago chiefly to those who discovered fire; to those who found and domesticated cereals and useful animals; to those who developed speech, with, much later, the

forms of writing; and to the rather few individuals whose similar and continued inventions and discoveries have given us the physical and factual equipment of the Earth and the mind of today. If this be true, it would follow that from this primary and truest standpoint the present world owes no normal civilized person anything. But, on the contrary, every modern man—and particularly every really educated and physically normal person—is under unpayable and overwhelming debt to those ancient nameless and unknown, and to a few more modern little known and little appreciated, exceptional and creative men who have in effect transformed a world and with it literally created modern man."

But the gains which these changes in the environment have brought involve also losses. For whereas primitive man had to keep on the alert, had to observe keenly, think quickly, and act promptly in meeting the impact of his immediate natural environment, modern man is relieved of this necessity. His environment is more and more protective, less and less a challenge, and so civilization has dulled if it has not removed the stimulus to thought. This stimulus must be restored. It can be restored through the schools.

For, continues Dr. Riddle, "The individual today is so variously regulated, the social, industrial, and economic relations are so involved, that, if opinions and prejudices of great groups are continually to diverge even within spheres of established fact, we cannot long hope for amicable or tolerable life together. It would seem that nations must educate for citizenship. They will be forced to forget the frills. In our United States I think there is now no more important task for enlightened leadership than that of placing a 4-year program of life science in all our high schools. Personally, I would rather assist in rendering such a program of study available to our future citizens than make an important scientific discovery."

Recently an eminent biologist was asked to join a group interested in the promotion of eugenics. He declined to cooperate on the ground that such efforts were premature, that no real progress can be made until the citizenry is sufficiently acquainted with elementary biology to understand the meaning and the value of eugenics.

"In the long last we can only, as it seems to me, put our confidence in education," said James R. Angell. "In this remote future, we may thus by education, and possibly by eugenics, breed up a race capable of approaching problems of the kind we are at present facing in a scientific mood and by scientific methods. Certainly it is to education that I believe we must look first and foremost for any fundamental change in the existing situation. Nor will education as we know it today suffice to accomplish the result. It must be something far more vital, inclusive, and thoroughgoing. Our formal education now touches a fragment only of the life of the ordinary citizen, for most persons it is completed in childhood or early adolescence, and, while life itself continues to educate all of us in a measure, the full potential resources of intelligence are rarely called forth by reason of lack of stimulation and exercise. . . . If science in any important sense is to affect the intellectual quality of civilization, then through education it must be woven into the essential fabric of our culture."

What is called for is not more technical training in science, and not merely the formal training in the schools, but a vast deal more interpretation. The diffusion of knowledge can be placed secondary only to discovery. Necessarily the discoverer must get his results first, but the interpreter should follow close—not as propagandist but purely in the role of transmitter, passing on the new-found truth in symbols that communicate but do not distort or exaggerate or selectively filter the meanings.

"The future of America is in the hands of two men—the investigator and the interpreter," said Glenn Frank.

"We shall never lack for the administrator, the third man needed to complete the trinity of social service. And we have an ample supply of investigators, but there is a shortage of readable and responsible interpreters, men who can effectively play mediator between specialists and laymen. . . . A dozen fields of thought are today congested with knowledge that the physical and social sciences have unearthed, and the whole tone and tempo of American life can be lifted by putting this knowledge into general circulation. But where are the interpreters with the training and willingness to think their way through this knowledge and translate it into the language of the street? I raise the recruiting trumpet for the interpreters."

It is more than information, more than formal culture, more than human interest and entertainment and a zest for the better known and therefore better appreciated world around us that these programs of teaching and diffusion and interpretation offer. It is a new point of view and a new way of thinking, and its logical result should be a new type of public mind. It is the type of mind that democracy must have if it is to endure; and, equally, it is the type of mind that dictators must dispense with, stamp out, and destroy the seeds thereof, if they are to endure. Lovers of democracy should be lovers of science. In democracy's struggle to exist in an increasingly alien world, in the battle between "We and They" which some believe to be inevitable, the cause of man has no more powerful ally than science, not only in its techniques, its processes, and its machines and skills, but also in its ideology.

4

In indicating the key role of science in our civilization, and in emphasizing the strategic importance of its discipline in the present troubled state of mankind, I am not unmindful of other values. I know "it is not wisdom to be only wise." Patriotism, capitalism, ecclesiasticism, aesthetics,

and many other human inventions have had their part in forwarding the long ascent from the caveman's cave to such civilization as we possess. Nor am I blind to limitations of science. Bertrand Russell has said, "Scientific technique is concerned with the mechanism of life; it can prevent evils, but cannot create positive goods. It can diminish illness, but cannot tell a man what he shall do with his health." Perhaps an endocrinologist would dispute this, but futures are still futures and we must be realists of the present and wary of, as well as grateful to, the specialist. Science has developed specialization to a degree almost bewildering. Methods of synthesis now need to be worked out; techniques of collaboration among sciences; and the human problems are more difficult than those of technology. One hearkens sympathetically to George Sarton's distinction: "I would never claim that science is more important than art, morality, or religion, but it is more fundamental, for progress in any direction is always subordinated to some form or other of scientific progress."

Suppose we approach our new-found knowledge of nature in this attitude of humility. The research results represent progress in many different directions—discoveries in the high atmosphere, in the stars, in the distant nebulae, in the invisible radiations that bombard us, in the deeps of the atom, in the interactions of sound waves, in the chemist's molecules and the biologist's living cells, the search for the mystery of life and the mind, for the secret of aging and death. All this accumulated knowledge represents technical progress. It becomes human progress when applied to serve human values.

Modern man is still plagued with fears: the fear of economic collapse which will mean poverty, the fear of disease which will mean death or disability worse than death, the fear of war which gathers into and totals in itself all the other dreads. The only one of these fears that has been approached with anything approximating the scientific

method is the second; and it is the only one in which any decided progress has been made. In fighting disease science has had a clear field and a free hand, for the most part, and the result is that many diseases have been wiped out of civilized communities completely. Methods of coping with other diseases have been developed to a high degree of certainty, and the average life span has been nearly doubled. The attack on diseases of old age and other organic failures proceeds today in many centers, and with encouraging signs. It would proceed more rapidly if the purse strings were less constricted—a statistician recently tallied the accounts and found that the American public spends more money to attend two major football games than goes into a year's cancer research in all the institutions now at work on this truly major human problem. It seems only a question of time and money expended in the pursuit, before all bodily ailments will yield to this discipline that Pavlov called the "omnipotent scientific method."

Can we regard our social, economic, national, and international ailments from a similar point of view? Yes, why not? It is only repetitious defeatism to reject the proposal with the excuse that the ills of the more complex body of society constitute problems enormously more difficult than those posed by the ills of the human body. Of course they are more difficult, but they are not more hopeless than some of our bodily problems once seemed. A surgeon in George Washington's time regarded a stomach or intestinal operation as an impossible project; the agonizing pain, the risk of severing a vital part, the bleeding, and other dangers, ruled internal organs off the list of operable parts. Less than a hundred years ago many leading British physicians were urging the abolition of surgical hospitals because they had become festering centers of gangrene infection which seemed ineradicable; "houses of death" Surgeon John Bell called them. And within our present century there were years when the physician's diagnosis of a

patient's sickness as diabetes was often tantamount to a death sentence. Today these "impossibles" have been overcome. Insulin has brought life and health to innumerable victims of diabetes. With the aid of anesthetics, antiseptics, x-rays, and other instrumentalities and skills that were unknown in Washington's day, the beneficent knife now brings relief to every part, and there is scarcely any organ so hidden or so vital that it is not amenable to modern surgery. Gangrene has been banished so completely that in 1915 Surgeon W. W. Keen was able to say to a gathering of Army medical men, "Today we do not even know the bacteriology of this foul disease. Since 1865 I have not seen a single case. There has been no opportunity to discover its germ if, as is probable, it is a germ disease. Lister made its return impossible." Surgeons serving in the World War found that the "foul disease" was only waiting; and with the crowding of wounded men together, there followed numerous cases of gas gangrene. But the main point remains unshaken, that Lister through his use of antiseptics brought medical science a powerful instrument for preventing disease.

Lister's work stemmed from Pasteur's, and Pasteur's was preceeded more than half a century by Jenner's discovery of an effective vaccination for smallpox. On that May day in 1796 when the eight-year-old James Phipps bared his arm to Jenner's scalpel, and the physician vaccinated the boy with matter taken from a vesicle of cowpox, man established a powerful defense against microbes—if we may use the term microbes to include the invisible virus of smallpox. It would have seemed insanity if Jenner had claimed that out of future experiments with vaccines would come a new and comprehensive branch of medicine, providing methods of control not only for smallpox, but also for hydrophobia, typhoid, diphtheria, and a string of other pestilences that have preyed on mankind from time immemorial. Of course Jenner made no such claim, for he had no such expectation.

But history gives us the hindsight to see what foresight might reveal—if man could look forward through time.

Perhaps it is naïve to believe that because small sallies have been won a great battle may be ventured. But such has been the way of the laboratory from its beginning. Indeed, "the strength of science lies in its naïveté," as G. N. Lewis has said. Perhaps if we were not blind to difficulties we should attempt less; and if our faith in small achievements were not out of proportion to their importance we should never have the confidence with which to push ahead to the larger problems. But larger problems eventually have been resolved by these tactics of accretion, and difficulties of mountainous magnitude have slowly crumbled and melted and eventually disappeared under the same treatment. So we need not slight nor disparage our strength, even though it lie in so frailly human a quality. And we need not shrink from any problem, no matter how diffuse or discordant.

5

The search for a basis for a sane internationalism is a task to which science seems fitted, above all disciplines and inventions of mankind. In the first place, science itself is an internationalism. No other human interest has been so successful in transcending the barriers of race, language, nationality, and class. In his Huxley Memorial Lecture, A. V. Hill called attention to the following instructions issued by the British Admirality to the captain of the *Rattlesnake*, the ship in which T. H. Huxley, "a surgeon who knew something about science," sailed in 1846 on a voyage of biological exploration:

"You are to refrain from any act of aggression towards a vessel or settlement of any nation with which we may be at war, as expeditions employed on behalf of discovery and science have always been considered to be acting under a general safeguard."

This incident is typical. Its attitude of tolerance and immunity rests on a second universal characteristic of science, namely, the practice of freely sharing the results of scientific research. If an Englishman discovers an island or wins a victory over a hostile people, the island becomes English territory and the victory extends the realm of the British crown. But if an Englishman discovers a vitamin or conquers a virus, the discovery becomes part of the imperishable possession of the human race, and his victory is a victory of mankind. Science is a commonwealth, literally. As Frederick Soddy has said: "The results of those who labor in the fields of knowledge for its own sake are published freely and pooled in the general stock for the benefit of all. Common ownership of all its acquisitions is the breath of its life."

From this state of affairs there arise naturally a common interest in the activities of science, a common pride of ownership in its accomplishments, and a common feeling of obligation to sustain and protect these soldiers and servitors of mankind. The only manifest approach to a world-state today is the Republic of Science. It may be described as a commonwealth of the mind, without territory, armies, diplomacy, or other political instruments of power; and yet it is the most powerful government on Earth.

The editor of *Nature* estimates that of the thirty million persons in the electorate of the United Kingdom, the workers in science and engineering number about thirty thousand—one-tenth of 1 per cent of the whole. Perhaps the same percentage would hold for the United States, but averaged over the whole Earth the proportion would be smaller. By eliminating the Republic of Science—it might be done by killing off this small percentage of the population and burning the books and other scientific records—the leaven of objective thinking would be so weakened that in effect it would be destroyed. Technologies would lapse, the

arts of medicine and engineering would flag, and civilization would retrogress into a primitive stage of scarcity, pestilence, hard labor, intensified competition, superstition, and cruelty.

If the withdrawal of science may work such hardships, it seems reasonable to infer that the extension of science may be used to soften existing hardships. We think of internationalism as the antithesis of militarism, and regard an acceptance of the idea of cohesion and the practice of cooperation in the sphere of interhuman relations as prerequisites to internationalism. Then science—international, cohesive, and cooperative, both in spirit and in practice—would seem to offer a measure of hope.

The "formulation of an agreed purpose for man as a whole will not be easy," grants Julian Huxley. "But let us not forget that progress *can* be achieved. After the disillusionment of the early twentieth century it has become fashionable to deny the existence of progress, as it was fashionable in the optimism of the nineteenth century to proclaim its inevitability. The truth lies between the two extremes. Progress is a major fact of past evolution; but it is limited to a few selected stocks. It may continue in the future; but it is not inevitable—man must work and plan if he is to achieve further progress."

Therefrom opens our outlook for a civilized Earth. If it seems a slender prospect, only a still small voice of hope hardly heard above the swish of the war machines and the noise of the orators, remember that the idea of purposed progress is new. There has been blind progress from the beginning; but, as James Harvey Robinson has said, it was not until within fairly modern times that man came to wish for progress, and "entirely within our own day that he has come to see that he can voluntarily progress." The discovery of the possibility of progress is a gift of science, perhaps its greatest gift. The largess continues with accelerating proof in our day, as the contemporary

news from the laboratories witness. The Promethean capture of fire is a prototype of what is happening now on every front. And we see that what at first was an individual gain, a man's triumph, becomes the highest progress when it is diffused, shared, universally applied to every need it can serve. Then it becomes mankind's triumph.

This is the promise—and, in a sense, the process—of science. Within the limits of nature's law, man is free to mold his future. By design he may increase the probability of a desired outcome. And so we say that destiny is a choice, a selection among alternative destinies. But the selection cannot be left to accident; it is not fortuitous, automatic, foolproof. Man himself must choose.

INDEX

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